ACCURACY OF DIGITAL ORTHOPHOTOS FROM HIGH RESOLUTION SPACE IMAGERY

Jacobsen, K.*, Passini, R. **

* University of Hannover, Germany
** BAE Systems ADR, Pennsauken, NJ, USA
jacobsen@ipi.uni-hannover.de
rpassini@adrinc.com

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ABSTRACT:

Today existing high resolution space imagery are entering into competition with the aerial photography for regional mapping programs and other extensive mapping applications where high resolution is required. The IKONOS and QuickBird imagery are typical examples. These are quite suitable for the production of Digital Orthophoto with resolutions of one meter or smaller. This paper analyses the effect on the accuracy of Digital Orthophotos been produced from these imageries and using different geometric projection models (i.e., Rational Functions, strict geometric model, interpolation models); number, distribution and quality of Ground Control Data and used DEM quality and geometric characteristics. Image matching and correlation potentials for the generation of DEMs are also included.

1. INTRODUCTION

The pixel size of IKONOS images is corresponding to the information content of aerial images with scale 1:80 000; the QuickBird images are even corresponding to aerial images 1:50 000. Such images are used for topographic mapping up to a map scale 1:10 000/1:6000. Orthoimages shall have 8 pixels/mm or more if the pixel structure shall not be visible. Based on this rule, IKONOS images can be used for orthoimages 1:8000 and QuickBird for 1:5000. With this specification we do have a direct competition of the very high resolution space images to aerial photos.

In addition to the aspect of information contents also the geometric accuracy potential is important. This is depending upon the exact identification of the objects in the images and the image geometry itself together with a sufficient mathematical model.

2. SENSOR INFORMATION

The details of the IKONOS geometry are explained in Büyüksalih et al 2003 and Jacobsen, Passini 2003. In general IKONOS and QuickBird do have very similar original image geometry. The satellite line scanner images do have the perspective geometry only in the CCD-sensor line. By theory for any CCD-line there is a different exterior orientation, but the relation of the exterior orientation to the satellite orbit is only changing slightly. So for the classical CCD-line cameras, the attitudes are not changing in relation to the satellite orbit in the siderial system. The earth is rotating in this system. The projection centers are located in the satellite orbit – this can be expressed as a function of the image component in the orbit direction.

The new sensors with a flexible view direction are able to change the view direction during imaging continuously with high precision. So the covered area can be chosen with a border line corresponding to the coordinate grid (“yaw control”) – the satellite can be rotated in a manner that the projected CCD-line will be located exactly in the east-west-direction and the roll can be changed permanently to reach a scene border line with a fixed east-value. The area covered by a SPOT-4-scene can be seen in figure 1. The northern boundary shows the direction perpendicular to the orbit, the east- and west-boundary are showing the orbit direction in relation to the rotating earth – by this reason, the northern and the western boundary are not perpendicular to each other.

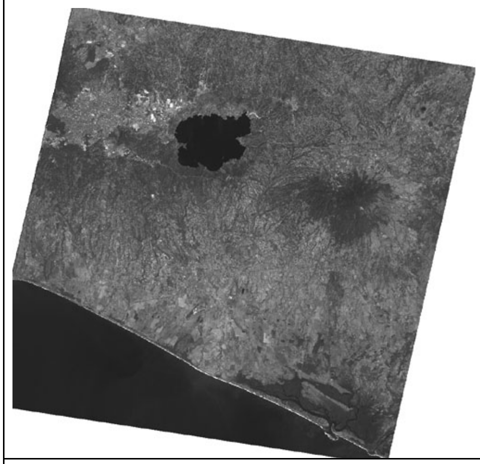

Figure 1:

area covered by SPOT 4 – scene

(SPOT 4-orthoimage)

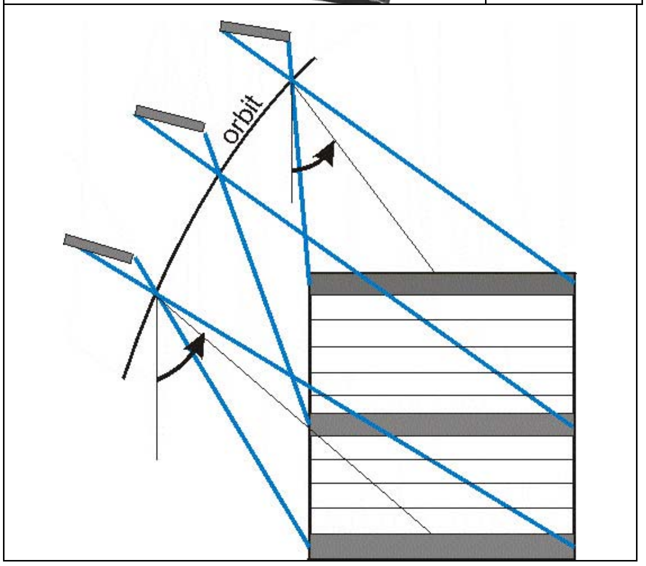

Figure 2: area covered by imaging with yaw control

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 taken by the individual CCD-lines. DigitalGlobe is naming it also as level 1B, but it can be compared with the geometry of level 1A SPOT images. It corresponds to the geometry taken by a unique CCD-line with 27552 panchromatic and 6888 multispectral elements without geometric distortion. The information about the focal length differs for the scenes, it is in the range of 8835mm in relation to the pixel size of 12 µm leading to 61cm pixel size in the nadir. In the orbit direction 6900 lines/second are taken supported by a transfer delay and integration sensor (TDI) – the reflected energy is summed up not only in one CCD-line but by shifting the generated charge corresponding to the image motion over a group of CCD-elements more energy is summed up. High-frequency attitude motion during the image acquisition is removed from the Basic Imagery, only the low frequency motion remains. The ephemeris and attitude data are delivered together with the images. The Basic Imagery can be handled similar to standard satellite line scanner images. It is possible to use the ephemeris included in the *.eph-file with geocentric coordinates and the attitude data included in the *.att-file as four-element quaternions. The quaternions describe the rotation of the camera relative to the ECF frame (Earth Centred Fixed = geocentric, rotating with the earth, in the WGS 84 reference system).

Also other products like the “Standard Imagery” also named as level 2A, are available, having a geometry similar to the CARTERRA Geo, but a pixel size of 70cm. Opposite to the IKONOS Geo-product, the Standard Imagery are not rectified to a surface with constant height but to the rough digital elevation model (DEM) GTOPO 30 which has a spacing of 30” with the exception of the polar regions. The 30” spacing are corresponding to approximately 900m. The vertical accuracy of the GTOPO30 is quite different depending upon the used source and area; DigitalGlobe is naming it with a standard deviation between 9m and 300m. So a geometric improvement by a satisfying DEM is required in addition to the exact geo-location which must be based on control points. This can be done similar to the IKONOS Geo-scenes also with the Hannover program CORIKON which is reconstructing the imaging geometry (Büyüksalih et al 2003).

3. IMAGE ORIENTATION

3.1 QuickBird

QuickBird Basic Imagery have been handled in the area of Phoenix, Arizona and Atlantic City, New Jersey. In the area of Phoenix, Digital Orthophoto Quarter Quads (DOQQ) of the USGS having 1 meter pixel size was used as a reference frame along with the corresponding 7.5’ USGS DEM. In the area of Atlantic City photogrammetric derived panchromatic orthophotos with a pixel size of 60 cm, based on aerial photos with a scale 1:19200 and a DEM with accuracy in the range of 50 cm was used.

Neighboured DOQQs are overlapping; in the overlapping area of the project Phoenix 112 corresponding points have been measured. The root mean square difference is +/-1.43m leading to an individual horizontal coordinate accuracy of +/-1.01m at the border area of the DOQQs. If the discrepancies would be based just on the used height information, the average influence for the whole DOQQ would be in the range of approximately +/-0.6m.

The Basic Imagery has been adjusted with the Hannover program for adjustment of satellite line scanner images BLASPO without using the ephemeris and attitudes. Just the general information about the satellite orbit together with the view directions has been respected, which is included in the *.imd-file as “in track view angle” and “cross track view angle”. Systematic effects caused by low frequency motions have been handled by self calibration with additional parameters. It was necessary to extend the set of used additional parameters for the special geometric characteristics of QuickBird.

```
Y = Y +  P1 * Y
X = X +  P2 * Y
X = X +  P3 * X * Y
Y = Y +  P4 * X * Y
Y = Y +  P5 * SIN(Y * 0.12566)
Y = Y +  P6 * COS(Y * 0.12566)
Y = Y +  P7 * SIN(Y * 0.06283)
Y = Y +  P8 * COS(Y * 0.06283)
Y = Y +  P9 * SIN(Y * 0.03100)
Y = Y + P10 * COS(Y * 0.03100)
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Y = Y + P11 * SIN(Y * 0.01600)
Y = Y + P12 * COS(Y * 0.01600)
X = X + P13 * SIN(Y * 0.03100)
X = X + P14 * COS(Y * 0.03100)
X = X + P15 * SIN(Y * 0.01600)
X = X + P16 * COS(Y * 0.01600)
X = X + P17 *SIN(X * 0.11)*SIN(Y*0.03)
X = X + P18 *XR*YR*COS(AKAP)
Y=Y+P18*XR*YR*SIN(AKAP)
Y = Y + P19 * X * X                IRS-1C/D PAN
X = X + P20 * Y * Y                IRS-1C/D PAN
X = X + P21 * (X-14.)   if x >  14.   IRS-1C/D PAN
X = X + P22 * (X+14.)   if x < -14.   IRS-1C/D PAN
Y = Y + P23 * (X-14.)   if x >  14.   IRS-1C/D PAN
Y = Y + P24 * (X+14.)   if x < -14.   IRS-1C/D PAN
```

Table 1: changed additional parameters of BLASPO

The additional parameters actually used by BLASPO have to be checked for their justification. BLASPO will automatically reduce the parameters specified by dialogue to the required group by a statistical analysis based on a combination of a Student-test, the correlation and total correlation. This guarantees that no over-parameterization is happening, so also an extrapolation outside the area covered by the control points is not dangerous.

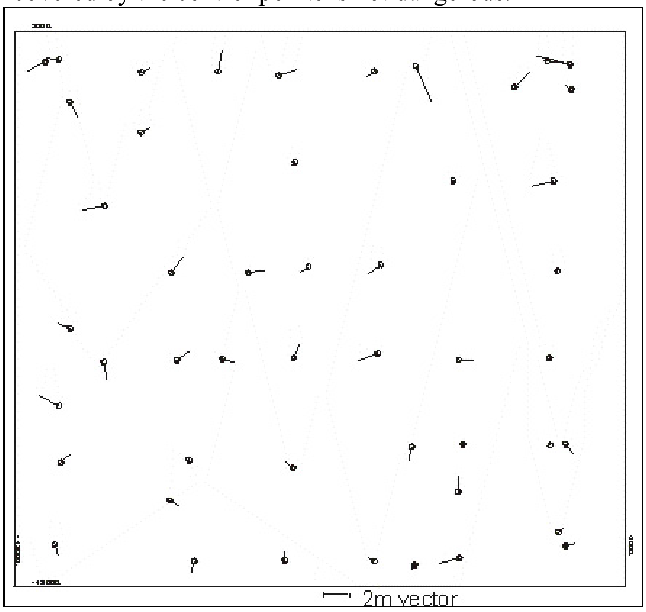

Figure 3: QuickBird scene 12450 - Phoenix, discrepancies at control points

	control points			check points	
scene	no.	RMSX [m]	RMSY [m]	RMSX [m]	RMSY [m]
12450	207	1.23	1.25		
12450	48	1.00	0.83		
12450	15	0.60	0.48	1.20	0.95
12450	13	0.64	0.51	1.28	0.94
12450	9	0.34	0.17	1.19	1.85
12451	55	1.27	1.18		

Table 2: root mean square discrepancies at control and check points, area: Phoenix

In the scene 12450 of the area Phoenix at first 48 control points have been measured by a human operator taking care about symmetric points. This was leading to root mean square discrepancies of RMSX=1.00m and RMSY=0.83m, corresponds to 1.5 pixel – a sufficient but not too good result. The main reason for the limited accuracy is caused by the used control points, they are not better. So this is not a check for the accuracy which can be achieved with QuickBird images. Another operator has measured 159 additional points, but he mainly used corner points. Corner points cannot be so accurate like symmetric points because the position always is shifting from the bright area to the dark. So only an RMSX=1.23m and RMSY=1.25m has been reached. This was similar in the scene 12451. A reduced number of control points (see table 2) was leading also to satisfying results at the check points respecting the situation of the not error free control.

In the area of Atlantic City a scene has been oriented by means of photogrammetric produced digital orthophotos with pixel size of 60 cm and a DEM with accuracy in the range of 50 cm. At first 174 control points have been measured manually, later 380 control points have been determined by automatic matching with SocetSet of the reference DOQQs with the QuickBird scene.

			control points		check points	
type of point observation	no. CP	σ0 [µm]	RMSE X [m]	RMSE Y [m]	RMSE X [m]	RMSE Y [m]
manually	174	14.6	0.85	0.64		
automatic	380	11.4	0.55	0.64		
automatic	25	14.1	0.49	0.74	0.69	0.72
automatic	20	13.4	0.53	0.56	0.69	1.39
automatic	15	19.0	0.54	0.96	0.78	1.38

Table 3: root mean square discrepancies at control and check points, area: Atlantic City

The achieved accuracy of the automatic matched points is better like for the manual measured points. The accuracy is reaching approximately 1 pixel – this seems to be an operational result, valid also for IKONOS-data. Of course with a smaller number of control points, the discrepancies at the independent check points are becoming larger, but this partially can be explained by the control point quality itself. On the other hand, with a smaller number of control points only a smaller number of additional parameters can be determined, enlarging the sigma0-value which describes the accuracy within the image – this has to be compared with the pixel size of 12µm.

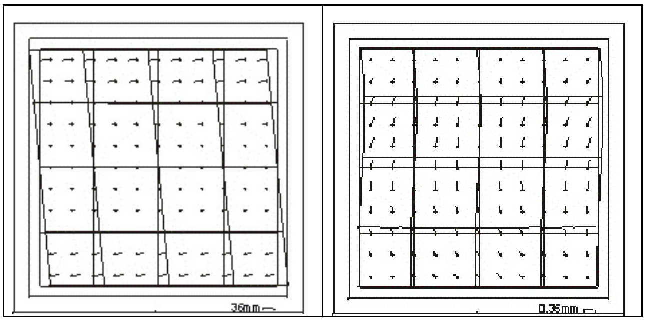

Figure 4: "systematic image errors" QuickBird Atlantic City – left: total effect, right: only not linear component

As it can be seen in figure 4 on the left hand side, the influence of the yaw control to the scene is covered by the additional parameters; it is reaching an angular affinity of 12.4°. The not linear effect on the right hand side of figure 4 shows the low frequency attitude influence to the scene.

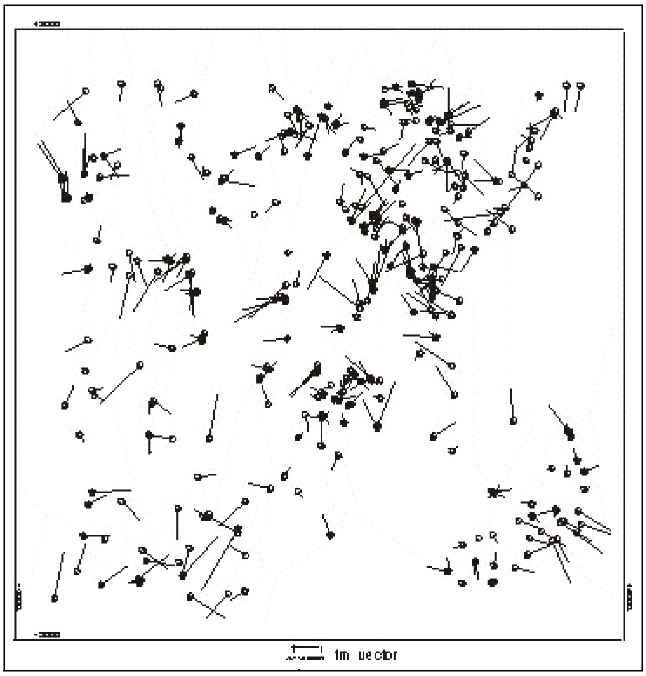

Figure 5: QuickBird Atlantic City – discrepancies at control points

QuickBird Standard Imagery does have a quite different geometry like the Basic Imagery. The Standard Imagery is rectified to the rough DEM GTOPO30. They have to be handled in the same manner like the IKONOS Geo-images with the difference that instead of the height difference against the reference plane, for the QuickBird Standard Imagery the height difference against the GTOPO30 has to be used. This has to be handled with different software like the Hannover program CORIKON.

3.2 IKONOS

Opposite to DigitalGlobe, SpaceImaging is distributing as lowest level product from IKONOS only the geo-referenced CARTERRA-Geo. The Geo-product is a geo-referenced rectification to a plane with constant height. It is similar to the QuickBird Standard Imagery with the difference of the reference height, which is only a plane with constant height. So the differences of the IKONOS-Geo to a map are larger like for the QuickBird Standard Imagery, but this is not important - in both cases a geometric refinement is required. The geo-reference is based on the direct sensor orientation, using the satellite position and view direction for each line.

SpaceImaging is not distributing the mathematical sensor model; instead of this the relation of the Geo-Image to the national coordinate system in form of rational polynomial coefficients is available. They do describe the scene position as the relation of a polynomial as function of the three-dimensional ground coordinates divided by another (formula 1).

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

Formula 1: rational polynomial functions

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.

The geometric improvement of IKONOS-Geo can be based on the rational functions distributed by SpaceImaging, a reconstruction of the image geometry, rational polynomial functions based on control points and 3D-affine transformation. Rational polynomial functions based on control points should be avoided; they do have poor error propagation and do require several control points (Büyüksalih et al 2003). A 3D-affine transformation does not respect the imaging geometry, requires a higher number of control points and has problems in mountainous areas. With the exception of some problems with the view direction included in the header data and also the rational polynomials distributed by SpaceImaging Eurasia, with the rational functions (Hannover program RAPORI) and the reconstruction of the imaging geometry (Hannover program CORIKON) approximately the same result has been achieved (Büyüksalih et al 2003). With control points determined by GPS-survey an accuracy of 0.9m identical to 0.9 pixels has been reached. In general 5 control points are sufficient for +/- 1.2 pixels.

In New Jersey under similar conditions like described above for QuickBird (control = DOQQ, height information from 7.5' DEM of the USGS), a root mean square difference for X of 1.45m and for Y of 0.98m has been reached. The X-component is depending upon the accuracy of the reference DEM which is very often the bottle neck for the positioning.

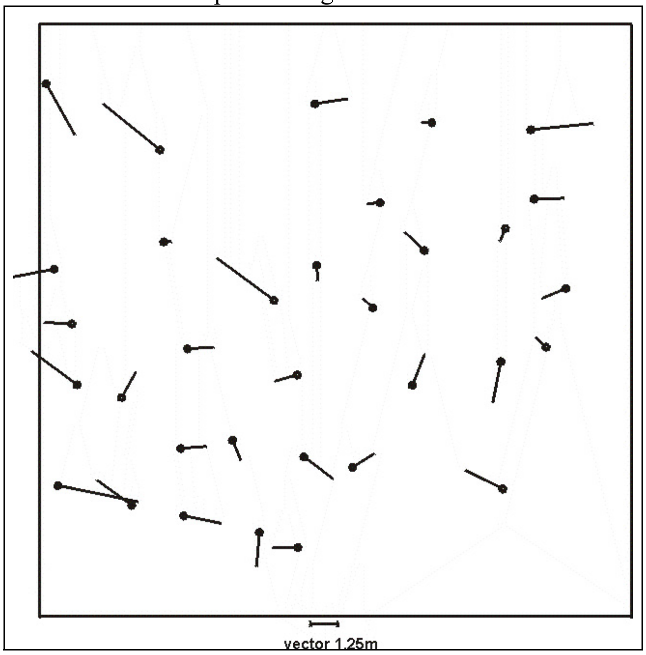

Figure 6: discrepancies at control points
IKONOS New Jersey, reference = DOQQ

4. GENERATION OF ORTHOIMAGES

The geometric quality of orthoimages is depending upon the orientation accuracy like described above and the used DEM. The digital elevation model also can be generated by automatic image matching of the space images, but only a limited number of stereo pairs are available in the archive and DigitalGlobe up to now does not accept orders for stereo pairs. The automatic matching of an IKONOS-stereo combination taken in the same orbit was leading with a standard deviation for the x-parallaxes of +/-0.22 pixels to excellent results. Quite more difficult it was for images taken with a time interval of 2 month with strong changes of the shadows. In this case the matching failed in the forest areas and also in the other areas it was poor.

From QuickBird two partially overlapping scenes taken with 10 days difference in time over suburbs of Phoenix, Arizona having a height to base relation of 9.1, 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 (see figure 7 left hand side) and the matching failed only in few limited areas with very low contrast like on roads, sandy areas and few roofs (figure 7, right hand side).

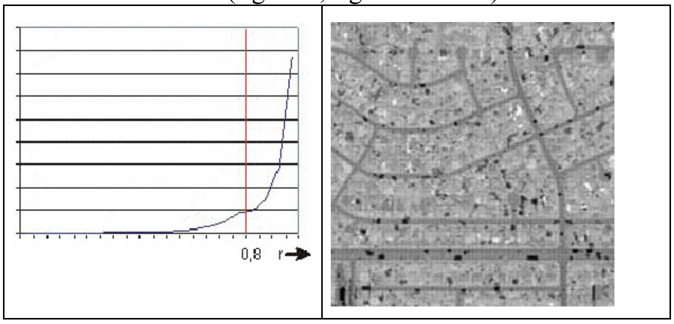

Figure 7: image matching of QuickBird images
left: frequency distribution of correlation coefficient
right: sub-image with overlaid matched points (dark = not matched)

By automatic matching a digital surface model (DSM) with points located on the visible surface of the objects will be generated. A DSM can be reduced to a DEM with points just located on the bare ground by automatic data analysis (Passini et al 2002), but this is not necessary for height models used for the generation of orthoimages if the spacing is small enough.

The height accuracy leads to horizontal discrepancies as a function of the tangent of the nadir angle. Required is usually a standard deviation of 2 pixels for the orthoimage X- and Y-location corresponding to +/-2m for IKONOS and +/- 1.2m for QuickBird if orthoimages with the full resolution shall be generated or in general 2 pixels of the created orthoimage. Respecting the error component of 1 pixel for the orientation, with a standard deviation of 4.8m for Z, orthoimages with 0.6m pixel size can be generated from images with a nadir angle up to 12° or if just orthoimages with 1m pixel size shall be generated, a nadir angle up to 37° can be accepted. But usually only existing DEMs are used for the generation of orthoimages based on the very high resolution space images. The required vertical standard deviation for the reference DEMs can be seen in table 4 which respects the error component for the orientation of 1 pixel. The allowed error component for the height can be computed with formulas 2 and 3; the results are shown in table 4.

$$SXl = \sqrt{SXortho^2 - SXo^2}$$

SXl =error component allowed as function of SZ
SXortho =standard deviation of orthoimage
SXo = standard deviation of orientation

Formula 2: standard deviation acceptable for the influence of the DEM to the horizontal location of orthoimages

$$SZallowed = \frac{SXl}{\tan \eta}$$

η = local nadir angle of space image

Formula 3: acceptable Z-standard deviation of the DEM for the generation of orthoimages

image	QuickBird		IKONOS
pixel size of orthoimage	**0.6m**	**1.0m**	**1.0m**
allowed SX	1.2m	2m	2m
SXl	1.06m	1.90m	1.73m
nadir angle η	SZallowed [m]		
5°	12.1	21.7	19.8
10°	5.7	10.8	9.8
15°	4.0	7.1	6.5
20°	2.9	5.2	4.7
25°	2.3	4.1	3.7
30°	1.8	3.3	3.0
35°	1.5	2.7	2.5
40°	1.3	2.3	2.1
45°	1.1	1.9	1.7

Table 4: allowed vertical standard deviation of the DEM used for the generation of orthoimages depending upon the local nadir angle of the space images and the pixel size of the orthoimage

Not only the geometric, also the radiometric quality of the space images is important. The radiometric quality of QuickBird and IKONOS images have been compared with DOQQs, the digital orthophoto quarter quads of the USGS, which are usually based on aerial images. In all cases, the radiometric quality of the very high resolution space images was quite better like the existing DOQQs. One reason for this is the extended range of the panchromatic IKONOS and QuickBird images which includes with a wavelength from 0.45µm up to 0.90µm also parts of the near infrared. The radiometric quality of QuickBird and IKONOS are the same – both satellites are equipped with very similar KODAK cameras.

CONCLUSION

The inner accuracy of the satellite line scanner images from IKONOS and QuickBird are in the sub-pixel range. If the image orientation will be determined with programs based on strict mathematical models, under operational conditions, the geometric limitation is not the geometric image quality; it is the very often limited quality of control points. This includes also the identification of the control points in the images. Polynomial solutions based just on control points should be avoided; they do require a higher number of control points, do have problems with the identification of blunders and do have poor error propagation in the region outside the control points. With the rational functions distributed by SpaceImaging the same accuracy like with the solution reconstructing the imaging quality has been reached with the exception of few cases where the orientation information and also the rational functions distributed by SpaceImaging Eurasia were not precise. This problem could be solved only with the program reconstructing the image geometry.

DEMs can be generated also by automatic image matching of the high resolution space images, but only few stereo combinations are available in the archives. The radiometric quality of the space images is under usual conditions in most cases better like for aerial images.

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