ACCURACY OF DIGITAL ORTHOPHOTOGRAPHY FROM HIGH RESOLUTION SPACE IMAGES

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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 QuickBird and the Ikonos imagery are typical examples. They are totally suitable for the production of digital orthophotography with resolutions of 1 meter or smaller. This paper includes an analysis of the effect on the accuracy of digital orthos been produced using these imageries and using different geometric projection models (i.e., Rational Polynomial Functions, rigorous geometric model and interpolation models); number, quality and distribution of Ground Control Points, used DEMs quality and geometric characteristics. The image matching potentials for the generation of Digital Surface Models is also analyzed.

1. INTRODUCTION

Accepting the rule of thumb for which in all topographic maps a pixel size of 0.05 to 0.1 millimetres are required, then for a Ground Sample Distance (GSD) or pixel size in the terrain of 1 meter a map at scale up to a scale 1:10,000 can be designed. If we consider a Ground Sample Distance (GSD) of 60 centimetres, then the larger map scale would be 1:6,000. These are cases of satellite Images Ikonos and QuickBird respectively. Also accepting the fact that in an ortho-image there should be a minimum of 8 pixels /mm (otherwise the image grain or pixilation becomes visible), then based on a GSD of 1 meter the ortho-image design scale can be as big as 1:8,000 and for a GSD of 0.6 m would be 1:4,800. In other words, from the resolution view point, using Ikonos images, it is possible to produce topographic maps up to the scale 1:10,000 and orthophotos 1:8,000. Instead, working with QuickBird imagery the scales could be as big as 1:6,000 and 1:4,800 respectively. In addition to the aspect of information contents, also the geometric potential is important. This is depending upon the precise identification of objects in the images and image geometry itself along with a sufficient mathematical model.

2. SENSOR INFORMATION

The details of the Ikonos geometry are explained in details in Jacobsen, Passini 2003. In general the Ikonos and QuickBird imagery have very similar image geometry. Both basically are satellite line scanner systems as such the image geometry is of the central projection type line image by line image. In this sense the exterior orientation parameters of each line image are different, but the relation of the exterior orientation to the satellite orbit is only changing slightly. Hence for the classical CCD-line cameras, the attitudes are not changing in relation to the satellite orbit in the sidereal system. The earth is spinning in this system. The projection centers are located in the satellite orbit – this can be expressed as a function of the image components in the orbit direction.
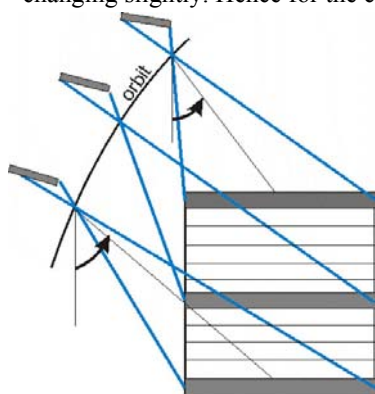
The new generation of sensors has the flexibility of changing view direction while acquiring the image. In this sense the sensors can change continuously the view direction in such a way that their image lines are located parallel to local or national East – West map projection grid direction. This is a continuous on the orbit changes of yaw and roll movement to reach the scene border line with a fixed east value. This is clearly shown in Figure 1

Unlike DigitalGlobe, Space Imaging does not distribute the Ikonos sensor model. Only the derived products can be acquired through its affiliate company

Figure 1

CARTERRA. A variety of products are possible; among them the most popular is the so called Geo-products. This is simply rectified imagery to a plane parallel to an ellipsoid and a cartographic projection system chosen by the client. As used is made of a plane parallel to the ellipsoid, the effects of the terrain relieve is still present. Moreover, the orientation of the geo-images is based on the on-board sensor readings, using the satellite positioning and view direction for each line that are enough for the precision to be reach by the geo-products, i.e., CE90 15 meters. See Figure 2
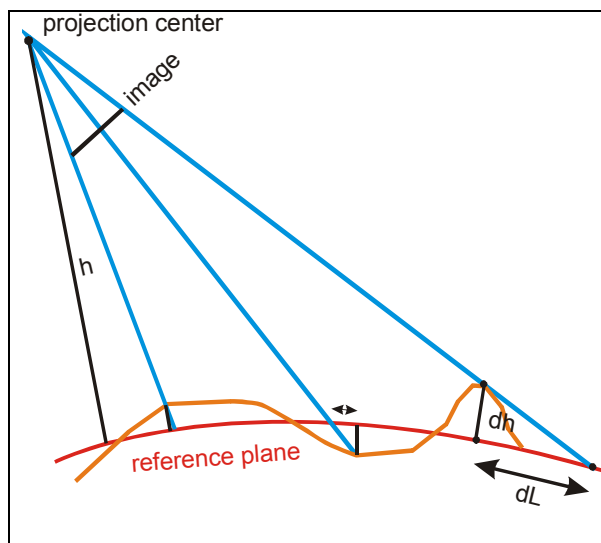

Figure 2

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 individual CCD-lines. DigitalGlobe is designating it as level 1B and it can be compared with the level 1A of Spot images. It is equivalent to the geometry being taken by a unique CCD-line scanner of 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 8835 mm for a 12 μm leading to 61 cm pixel size in the nadir. Within the orbit direction 6900 lines/second are being taken supported by a transfer delay and integration (TDI) sensor. The reflected energy is summed up not only in one CCD-line but by shifting the generated charge in correspondence to the image motion over a group of CCD-elements. High frequency attitude motions during the image acquisition is removed from the Basic Imagery

and only low frequency disturbances remains. Along with the images, the ephemeris and attitude data are delivered. For the image orientation it is possible to use the ephemeris data included in the *.eph file with respect to geocentric system and the attitude data included in the *.att represented as a four-element quaternions. These describe the attitude of the camera with respect to a Earth Center Fixed (ECF) geocentric, rotating with the earth.

Other two products are also distributed by DigitalGlobe. One the so called "Standard Imagery", have geometry similar to the CARTERRA Geo with a pixel size of 71 cm. The main difference is that the rectification surface of the Standard product is a rough Digital Elevation Model, the GTOPO 30 that has a point spacing of 30" or approximately 900 meters. The main disadvantage of the GTOPO 30 is its low vertical accuracy – reliability. This can range between 10 to 450 m. Hence it is necessary to carry out a geometrical improving by using a satisfactory DEM in addition to the use of Ground Control Points (GCPs) for a precise geo-location.

The last product been released by Digital Globe is the "Ortho Ready" geometrically speaking this is very similar to the Geo-product of CARTERRA that is rectification to a constant plane in a cartographic projection system been chosen by the customer.

3. IMAGE ORIENTATION
3.1. Ikonos

Opposite to DigitalGlobe, Space Imaging is distributing as lowest level product from Ikonos only the Geo-referenced CARTERRA-Geo. This is a simple rectification to a plane with constant height. Hence the CARTERRA-Geo are influenced by the local terrain elevations. A height difference dh against the height level of rectification is causing a shift dL See Figure 2 and 3

$$dL = dh * \tan(\text{local nadir angle})$$

In addition the geo-reference of the geo-scene has to be improved by means of control points. The geo-referencing is based on direct sensor orientation of the Ikonos satellite based on GPS-positioning and a combination of inertial measurement system together with star sensors.
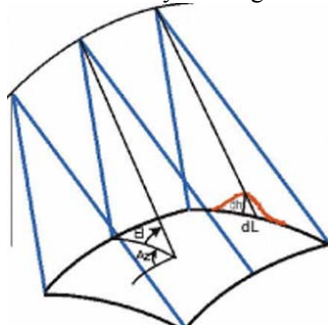
The absolute geo-reference without control points is claimed in the specifications with a Standard Deviation of 12m. Dial and Grodecki (2002) from Space Imaging are reporting a higher accuracy in the range of 4m, but it is not normal distributed. This range can be confirmed, but under operational conditions it is very often difficult to get information about the local datum of the national coordinate systems.

As mentioned the sensor model is not available for distribution for Ikonos images. Instead Space Imaging is distributing the relation of the Geo-Images to the national (or State Plane) coordinate system in form of Rational Polynomial Functions. They describe the scene position as the relation of a polynomial as function of the three-

Figure 3: Geometric Condition of Geo-images

dimensional coordinates divided by another. See formulas bellow:

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

$$P_{il} = a_1 + a_2.Y + a_3 X + a_4 Z + a_5 XY + a_6 YZ + a_7 XZ + a_8 Y^2 + a_9 X^2 + a_{10}Z^2 + a_{11}XYZ + a_{12} Y^3 + a_{13}YX^2 + a_{14} YZ^2 + a_{15}Y^2X + a_{16}X^3 + a_{17}XZ^2 + a_{18}Y^2Z + a_{19}X^2Z + a_{20}Z^3$$

The horizontal ground coordinates are handled as geographic coordinates. Third order polynomials are used. Hence 80 coefficients are used to relate the Ground Coordinates System and the Geo-image coordinate system. Space Imaging is adjusting the rational polynomial coefficients 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 model. They have the advantage that for the transfer of the image orientation to and from photogrammetric workstations that it is not necessary the workstation to have built in the sensor model.

Another possibility of handling the Ikonos Geo-images is through the reconstruction of the image geometry as it is done by the program system CORIKON. Within the data header of each Geo-image, the view direction from the scene center to the satellite is available in terms of the Nominal Collection Elevation and Azimuth (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 that has been published. Hence, the individual projection center for any image position can be computed. This has to respect the scan direction along or against the orbit. See figure 4.
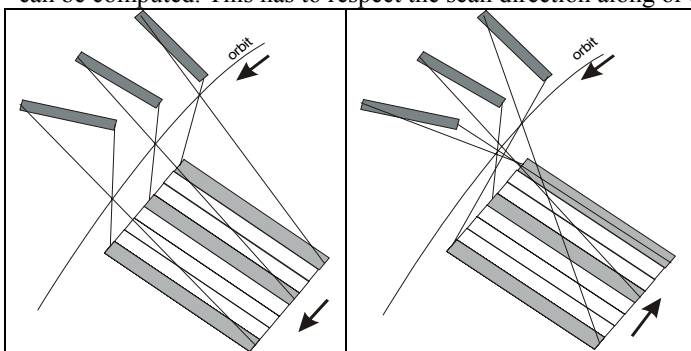
The required information is available as "scan azimuth" in the header data, where scan azimuth 180° means the scan with the satellite motion and scan 0° means the imaging against the satellite motion. The influence of the scan direction to the adjusted coordinates is limited to negligible.

The final geo-positioning is carried out by using a 2-D Affine transformation (6 unknowns) using GCPs. With control points determined by GPS measurements an accuracy of 0.9 m identical to 0.9 pixels has been reached. In general 5 GCPs are sufficient for ± 1.2 pixels.

Figure 4: 180° degree scan   0°degree scan

In New Jersey (Williamstown area) using GCPs been transferred from DOQQs and height information interpolated from a 7.5' USGS DEM a root mean square difference for X of 1.45 m and for Y of 0.98 m 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. In the area of Zanguldak – Turkey, two Ikonos geo-scene were analyzed with different methods. 39 GCPs were determined by GPS, they are located between 217 m and 652 m above MSL. For one scene also RPC
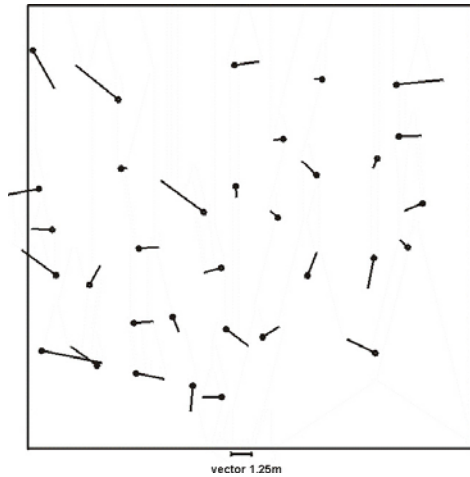
were available. This scene has been adjusted with the Hannover program CORIKON, reconstructing the image geometry, with the program RAPORI, based on RPC and with the PCI satellite modeling that is also based on RPCs. See results on Table 1

	RMSX	RMSY
RAPORI, RPC + 6 unknowns	5.20	1.04
CORIKON, reconstruction of geometry + 6 affine parameters	5.33	0.86
PCI satellite modeling (RPC)	5.85	0.82
CORIKON, 8 unknowns	1.01	0.80

Table 1. Results at 2 Ikonos Geo-scenes at Zanguldat - Turkey

Fig. 5: Discrepancies at GCPs. Ikonos – NJ area

As it can be seen from table 1, the results of the 3 solutions are similar. The slightly larger value for the PCI solution is based on an independent point measurement which can not be compared directly with the other solutions. The larger 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 the view direction. This resulting in a change of the nominal collection azimuth of 8.6°, which is with a Student Test of 31 very significant. The nominal collection elevation changed only 0.4°, this is also significant but not in so high level. This problem has also been notice in several oriented Ikonos geo-scenes and solved by introducing the nominal collection elevation and azimuth as unknowns within the adjustment. All unknowns in program CORIKON, are checked against 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 orientation if they are highly correlated and/or not significant. This may happen if all control points are located in approximately the same high level. In the Zanguldak area the adjustment of the view direction has drastically improved the results even to values slightly bellow the pixel size of 1 m.

3.2 QuickBird

QuickBird Basic Imagery within the area of Phoenix – Arizona and Atlantic City – New Jersey has been oriented. In the area of Phoenix, Digital Orthophoto Quads (DOQQs) of the USGS having a GSD of 1 m ware used as a reference frame along with the corresponding 7.5' USGS DEM. In the area of Atlantic City, photogrammetric derived panchromatic orthophotos with pixel size of 45 cm at scale 1:19200 (1"=1600') and a DEM with accuracy in the range of the 50 cm were used.

Neighbored DOQQs are overlapping. In the overlapping area of Phoenix, 112 corresponding points were measured. The Root Mean Square Difference of Coordinates was ±1.43 m 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 of the whole DOQQ would have been in the range of approximately ± 0.6m.

All QuickBird Images have been least squares oriented with the Hannover Program for satellite line scanner images BLASPO without using ephemeris and attitudes as input data. Instead the general information about the satellite orbit together with the view direction was used. These are included in the *.imd-file as "in track view angle" and "cross track view angle". The systematic effects caused by the low frequency motions were removed by the self calibration approach through the use of additional parameters. It was necessary to extend the set of used additional

parameters to accommodate the special geometric characteristics of the QuickBird images. The set is shown in the table 2

```
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)
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 (KAPPA)
Y = Y + P18 *XR*YR*SIN (KAPPA)
Y = Y + P19 * X * Y
X = X + P20 * Y * X
X = X + P21 * (X-14.)
```

The additional parameters been used by the orientation program BLASPO has to be checked for numerical stability, statistical significance and reliability in order to justify their presence and to avoid over parameterization. The program will automatically reduce the parameters specified by dialogue to the required group by a statistical analysis based on a combination of Student-test, the correlation and total correlation. This guarantees that no over-parameterization occurs; in that case an extrapolation outside the area covered by control points does not become dangerous.

The elimination process is as follows:

1. For each additional parameter compute

$$t_i = \frac{|p_i|}{\sigma_{pi}} \quad ; \quad \sigma_{pi} = \sqrt{q_{ii}} \cdot \sigma_o \qquad t_i \geq 1 \quad \text{reject if otherwise}$$

2. Compute Cross-correlation coefficients for the parameters

$$R_{ij} = \frac{q_{ij}}{\sqrt{q_{ii} \cdot q_{jj}}} \qquad R_{ij} \geq 0.85 \quad \text{then eliminate the parameter with}$$

smaller t_i value

3. Compute $B = I - (\text{diag } N * \text{diag } N^{-1})^{-1}$, eliminate the add.
   Parameter that $B_{ii} \geq 0.85$

Figure 5 shows the discrepancy vectors after an orientation of a QuickBird Image (12450) in the area of Phoenix – Arizona and Table 3 contains the results in terms of root mean squares discrepancies at GCPs of scenes in the same area and for different number and distribution of GCPs.
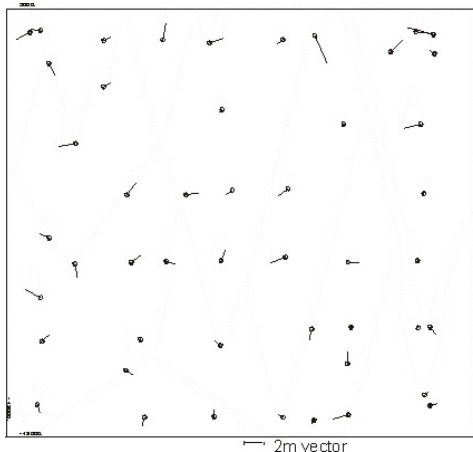

Figure 6. QuickBird Scene 12450.

		Ground Control Points		Check points	
Scene	No.	RMSX [m]	RMSEY [m]	RMSX [m]	RMSEY [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 3: Root mean squares discrepancies at GCPs and Check Points.QuickBird Scene 12450. Area of Phoenix – Arizona

In the scene 12450 of the area of Phoenix, 48 points were transferred and measured from the corresponding DOQQs. This operation was done manually using simple procedures of manual digitization. Care was taken in trying to pick up symmetric shape features as GCPs. This lead to root mean square discrepancies of RMSX = 1.00m and

RMSY=0.83m, corresponding to 1.5 pixel – a sufficient but not too good results. The main reason for the limited accuracy is caused by the pour quality of the control points. They can not be better. They are transferred points from USGS DOQQs with interpolated heights using also a 7.5' USGS DEM. Hence, this is not a check for the accuracy that is possible to be achieved by the use of QuickBird satellite images.

Another set of measurements of 159 points was carried out by another technician, but using mainly corner points of features. Corner points cannot be so accurate than the symmetric features because the position always is shifting from the bright area to the dark area. So only a RMSEX=1.23m and a RMSEY=1.25m was achieved. This was similar in the scene 12451. A reduced number of control points was (See table 3) has lead to satisfactory results at the check points having in mind the fact that neither the GCPs nor the check points are error free.

Type of Observation	No. GCPs	σ_o [μm]	GCPs		Check Points	
			RMSX [m]	RMSY [m]	RMSX [m]	RMSY [m]
Manual	174	14.6	0.85	0.64		
Automatic	398	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 4: Root Mean Squares Discrepancies at GCPs & Check Points
        Area of Atlantic City, New Jersey

In the area of Atlantic City a scene has been oriented by means of extracted and transferred points from photogrammetrically produced digital orthos with pixel size of 0.60m and a DEM with an accuracy of approximately 0.50m. Firstly 174 have been measured manually; later 398 GCPs were determined by automatic matching with Socet Set of the reference digital orthos with the QuickBird scene.

The achieved accuracy of the automatically matched points is better than the attained by the manually measured and transferred points from reference digital orthos. The accuracy is reaching approximately 1 pixel – this seam to be an operational result, valid also for the Ikonos images. Nevertheless, we notice that with smaller number of GCPs, the discrepancies at check points are becoming larger, but this is partially explained by the control point quality itself and by the fact that with smaller number of GCPs the reliability of the determination of the values of the additional parameters becomes lower and consequently the standard deviation (σ_o) becomes larger. See Table 4 above.
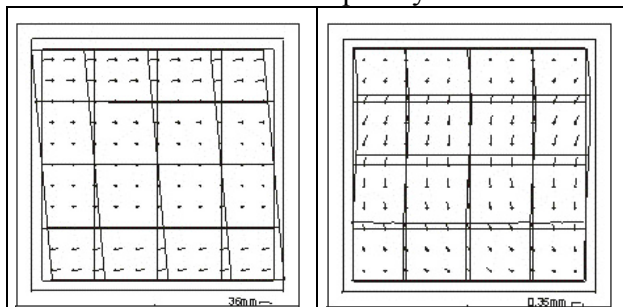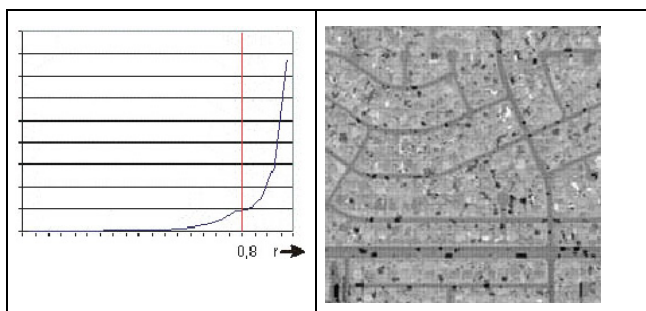

As it can be seen in the left hand side of Figure 7, the influence of the yaw control to the scene is covered by the additional parameters. This is reaching and angular affinity in the order of 12.5°. The non linear effect on the right hand side of figure 7 shows the low attitude frequencies to the scene. These are also being removed by the included additional parameters (See formulation above) and tested for over-parameterization based on the statistical procedures explained above.

DigitalGlobe commercialize also 2 other types of ima

Figure 7: Systematic image error. QB. Atlantic City, NJ.   ges, i.e., the Standard and the Ortho Ready. Both types have different geometry as compared with the Basic Imagery. The standard imagery is rectified to a rough DEM, the GTOPO30. They have to be oriented like the IKONOS Geo-images with the difference that instead of the height difference against a reference plane, for the QuickBird Standard Imagery the height difference against the GTOPO30 has to be used. In the case of the Ortho Ready, this is precisely the case of the IKONOS Geo-products. Both types of images can be handled by the program package CORIKON.

4. GENERATION OF ORTHOIMAGES

The geometric accuracy quality of an ortho-imagery depends on the accuracy of the orientation, as explained above and on the geometrical quality and resolution of the used Digital Terrain Model for its production. This can also be done using space images and automatic matching strategies, but until now there are only a few QuickBird stereoscopic pairs in the DigitalGlobe archive and up to now no orders for acquisition of stereo-pairs are accepted.

In the New Jersey area, the automatic matching of an IKONOS-stereo combination taken in the same orbit was leading to a standard deviation for the x-parallaxes of ±0.22 pixels, which represent excellent results. A quite different scenario was the results of image matching of two images taken with a time interval of 2 months. The reasons were different length of shadows, tree foliage, etc., between the two images. The matched points had an accuracy of just ±5.8m and with a base to height ratio of 3.9, this corresponds to a standard deviation of the x-parallax of $\sigma_{px}=\pm1.5$ pixels. The y-parallax of the matching reached $\sigma_{py}=\pm2.2$ pixels, demonstrating also the problems.

From QuickBird, two partially overlapping images taken with 10 days difference in time over the suburbs of Phoenix-Arizona, having a very bad height to the base ratio of 9.1, have been used for generation of a DTM. In the pair, the change in the vegetation and the sun elevation angle were negligible, hence good conditions for image matching existed. The automatic image matching gave excellent results with a vertical accuracy of ±4.8m in relation to a 7.5' USGS DEM that is not free of errors. 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 8). The matching failed only in few limited areas with very low contrast like roads, sandy areas and a few roofs.

Figure 8: Image matching of QuickBird Images.
Left: Frequency distribution of Correlation Coefficients
Right: sub-image w/overlaid matched pts (dark=not matched)

By automatic matching a Digital Surface Model (DSM) with points located on the visible surface of the objects is generated. The DSM is then reduced to a DEM with points just located on the bare terrain by means of filtering techniques (Passini et all 2002). In general this is not highly necessary for production of digital orthos from images taken from the space if the spacing is small enough.

Allowing for the orientation of the satellite scene no more than the pixel resolution and if no more than two pixels are allow for the accuracy of the final digital ortho, then the required accuracy of the DEM to be used for the ortho-rectification will depend on the nadir inclination angle of the satellite image.

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

SX_{xz} =error component allowed as function of S_Z
SXortho =standard deviation of orthoimage
SXo = standard deviation of orientation

Formula 1: standard deviation acceptable for the influence of the DEM to the horizontal location of orthoimages

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

η = local nadir angle of space image

Formula 2: acceptable Z-standard deviation of the DEM for the generation of ortho-images

Table 5: Accuracy requirements of the DEM

image	QuickBird		IKONOS
pixel size of orthoimage	**0.6m**	**1.0m**	**1.0m**
S$_{ORTHO}$	1.2m	2m	2m
SX$_{XZ}$	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 6: Accuracy requirements of the DEM as a function of the scene inclination angle and fixed ortho accuracy

The formulations of Table 5 and the numerical results of Table 6 shows that for a given accuracy specification of the final digital ortho, the allowed accuracy of the DEM to be used for the ortho-rectification is inversely proportional to the tan of the nadir angle of the scene.

5. CONCLUSIONS

The inner accuracy of the satellite line scanners Ikonos and QuickBird are in the sub-pixel range. When the image orientation is determined using the corresponding rigorous models, under operational conditions, the geometrical limitations are not due to the geometric image quality but to the quality and accuracy of the GCPs. This includes to the identification of the GCPs in the scenes. Polynomials solutions based on just control points should be avoided. They require a higher number of GCPs and they have poor error propagation in the region outside the control points. If use is made of the Rational Polynomial Coefficients distributed by Space Imaging not enough accuracy is obtained. This can be improved by the reconstruction of the image geometry through the use of GCPs a DEM and the 6 parameters affine transformation. This can be further improved if the Nominal Collection Elevation and Azimuth are introduced in the Adjustment as unknowns. To avoid over parameterization all computed parameters shall be tested for significance.

DEMs can also be generated using high resolution space imagery using automatic image matching. Usually when the estereo-images are taken within the same orbit or with short time interval between them, the image matching produced better results as compared when aerial photography pairs are used. This is because under usual conditions, the radiometric quality of the high resolution space imagery is better than the aerial photography.

6. REFERENCES

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