

ACCURACY ANALYSIS OF DIGITAL ORTHOPHOTOS FROM VERY HIGH RESOLUTION IMAGERY

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ABSTRACT:

The generation of digital Orthophotos now days can be done with aerial, but also very high resolution space imagery. For a real competition the geometric and radiometric quality has to be on the same level. Different QuickBird images have been used for the generation of orthophotos with 1m pixel size. The whole procedure from the orientation up to the final step has been analyzed in detail. Rational polynomial coefficients (RPC) and bundle orientation using orbit information was used for the handling of QuickBird Basic and Standard Imagery. The special problems of individual and combined scenes are analyzed.

QuickBird Images covering quite different areas were used. The effect of varying control point distributions on the accuracy, determined with independent check points was studied. Different sources of ground control like digital orthophoto quads, existing information from airborne photo flights and GPS-control points have been used. The required height information came from different digital elevation models (DEM) and ground survey. Satisfying results have been achieved.

1. INTRODUCTION

Accepting the rule of thumb for which in topographic maps a pixel size of 0.05 to 0.1 mm in the map scale is required, with a Ground Sample Distance (GSD) or a pixel size in the terrain of 61 cm a map at a scale up to 1:6,000 can be designed. Also accepting the fact that in an ortho-image there should be a minimum of 8 pixels/mm (otherwise the pixilation becomes visible), then based on a GSD of 60 cm the ortho-image design scale can be as big as 1:4,800. 61cm is the nominal GSD of the QuickBird B/W Panchromatic band for a nadir view, hence when working with this satellite imagery, maps up to a design scale of 1:6,000 and orthophotos of 1:4,800 are possible. 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 the image geometry itself along with a sufficient mathematical model.

In the present investigation different available mathematical models for the ortho-image generation using QuickBird imagery have been studied. Different sources of Ground Control Point (GCP) information, different number and distribution of GCPs, different number and arrangement of images and different environmental scenarios (i.e., dry urban desert, humid farming areas) have been included in the study.

2. SENSOR INFORMATION

Basically the QuickBird Images are of line scanner type. As such the image geometry is central perspective in the line direction. In this sense the exterior orientation parameters of each line are different, but the relationship 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. The Earth is spinning in this system. The projection centres 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 change of the yaw and roll movements to reach the scene border line with a fixed east value. This is shown in Figure 1.

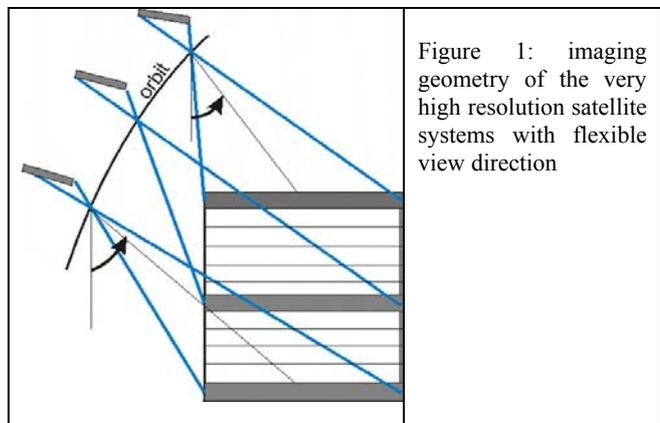


Figure 1: imaging geometry of the very high resolution satellite systems with flexible view direction

One product of the QuickBird Imagery is the so called “Basic Imagery” that is close to the original sensor image. The basic imagery is a sensor corrected merged image taken by a combination of shorter CCD-lines. DigitalGlobe is commercializing it as level 1B and it can be compared with the level 1A of Spot images. It is very close to the geometry taken by a unique CCD-line of 27552 panchromatic and 6888 multispectral pixels without geometric distortion. The information regarding the focal length differs for the scenes; it is in the range of 8835 mm leading the 12 μm pixel size to 61cm ground pixel size in the nadir. Within the orbit direction 6900 lines/second are being exposed supported by a Transfer Delay and Integration (TDI). 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 of the platform during image acquisition are removed from the basic imagery and only low frequency disturbances remains. Along with the images, the ephemeris and the attitude data are delivered. The ephemeris data can be used for the orientation of the image by making use of the ephemeris data included in the *.eph file with respect to a geocentric system and the attitude data included in the *.att file represented by four-element quaternions. These four parameters describe the attitude of the camera with respect to a Earth Centre Fixed (ECF) geocentric system, rotating with the Earth.

DigitalGlobe distributes also two other image products. The so called “Standard Imagery” is a projection of the image to the rough Digital Elevation Model GTOPO 30 having a point spacing of 30” or nearly 900 meters. The panchromatic image has a ground pixel size of 61cm. The main disadvantage of the GTOPO 30 is its low vertical accuracy. This can range between 10 to 450 m. Hence it is necessary to carry out a geometrical improvement by using an acceptable DEM in addition to the use of GCPs for a precise geo-location.

The other commercialized imagery product is the “Ortho Ready”. Like the Carterra Geo it is a projection of the image to a plane with constant height, available in a cartographic projection been selected by the customer. It has the same ground pixel size like the Standard Imagery.

3. IMAGE ORIENTATION MODELS

Depending on the type of QuickBird image being handled, different orientation models can be used, namely: For Basic Imagery, orientation can be done using a) Bundle Approach and b) Rational Polynomial Coefficients (RPCs). In the case of the of handling the Standard Imagery and Ortho Ready Products to improve their orientation and geo-referencing the affinity transformation based on GCPs including corrections for relieve displacement (through DTM) and improvements of the nominal collection elevation and azimuth (when justifiable) is the recommended procedure. Details regarding this last method are explained in details in Büyüksalih G., et all (2003); Jacobsen, K., Passini, R. (2003); Passini, R., Jacobsen, K. (2003); Passini, R. (2003).

3.1 Bundle Orientation with Self Calibration

The Bundle Model is based on the widely known collinearity equation in the CCD-line direction. The image position in the orbit direction is expressing the change of the exterior

orientation as a function of the orbit. As aforementioned, the exterior orientation parameters of each line image are different, but the relationship 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. Hence for an image it is possible to consider time (space) dependent attitude parameters. Taking into consideration the general information about the view direction of the satellite, the “in track and across track view angles” (included within the *.imd-file) and knowing that in a basic imagery the effects of the high frequency movements have been eliminated, then the effects of the low frequency motions of the platform can be modelled by self calibration via additional parameters.

The additional parameters been used by the Hannover orientation program BLASPO are checked for numerical stability, statistical significance and reliability in order to justify their presence and to avoid over-parameterization. The program 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 not 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:

$$t_i = \frac{|p_i|}{\sigma_{p_i}} ; \sigma_{p_i} = \sqrt{Q_{ii}} \cdot \sigma_0, t_i \geq 1, \text{ reject if otherwise}$$

2. Compute Cross-correlation coefficients for the parameters

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

smaller t_i value

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

3.2 Bundle Orientation using Ephemeris and Attitude Quaternions

The Camera Sensor Model distributed by DigitalGlobe is such that contains five coordinates systems, namely: Earth Coordinates (E), Spacecraft Coordinates (S), Camera Coordinates (C), Detector Coordinates (D), Image Coordinates (I). Definitions and details regarding these systems can be found in DigitalGlobe QuickBird Imagery Products, Product Guide.

The data contained in the Ephemeris File are sample mean and covariance estimates of the position of the spacecraft system relative to the ECF system. These files are produced for a continuous image period, e.g., an image or strip, and span the period from at least four seconds before the start of imaging after the end of imaging.

The attitude file contains sample mean and covariance estimates of the attitude space craft system relative to the ECF system. The instantaneous spacecraft attitude is represented by four-element quaternion. It describes a hypothetical 3D rotation of the spacecraft frame with respect to the ECF frame. Any such a

3D rotation can be expressed by a rotation angle, θ , and an axis of rotation given by unit vector components (ξ_x, ξ_y, ξ_z) in the ECF frame. The sign and rotation angle follows the right-hand rule. Finally the quaternion (q_1, q_2, q_3, q_4) is related to θ and (ξ_x, ξ_y, ξ_z) by:

$$\begin{aligned} \mathbf{q1} &= \xi_x \sin(\theta/2) \\ \mathbf{q2} &= \xi_y \sin(\theta/2) \\ \mathbf{q3} &= \xi_z \sin(\theta/2) \dots \dots \dots (2) \\ \mathbf{q4} &= \cos(\theta/2) \end{aligned}$$

The image lines in the Level 1B product are sampled at a constant rate. This means that the imaging time can be computed directly from the given data avgLineRate (Average Line Rate) and firstLineTime (First Line Time) with no approximations:

$$t = t / \text{avgLineRate} + \text{firstLineTime} \dots (3)$$

One point on the imaging ray is the perspective centre of the virtual camera at time t . The coordinates of the perspective centre in the spacecraft coordinate system are constant and given data. In matrix notation:

$$\mathbf{C}_s = (C_x, C_y, C_z)^T \dots \dots \dots (4)$$

Where C_x, C_y and C_z are values in the camera calibration file (*.geo file). It is possible to locate the origin of the spacecraft coordinate system in the ECF system at a time t by interpolating the position time series in the ephemeris file. Let us call this position $S_E(t)$. Likewise, we can find the attitude of the spacecraft coordinate system at a time (t) in the ECF system by interpolating the quaternion time series in the attitude file. This quaternion, $q^S_E(t)$, represents the rotation from the ECF system to the spacecraft body system at time t . Then using quaternion algebra, the position of the perspective centre at time t in the ECF coordinate system is:

$$\begin{aligned} \mathbf{C}_E(t) &= (\mathbf{q}^S_E(t))^{-1} \mathbf{C}_s \mathbf{q}^E_S(t) + S_E(t), \quad \text{or} \\ \mathbf{C}_E(t) &= \mathbf{q}^S_E(t) \mathbf{C}_s (\mathbf{q}^E_S(t))^{-1} + S_E(t) \dots \dots \dots (5) \end{aligned}$$

Alternatively, computing $\mathbf{R}^E_S(t)$, the rotation matrix from the given quaternions $q^S_E(t)$ for time (t) as a rotation from the spacecraft body to the ECF, then (5) above can be expressed by:

$$\mathbf{C}_E(t) = \mathbf{R}^E_S(t) \mathbf{C}_s + S_E(t) \dots \dots \dots (6)$$

Expressions (5) and (6) are the position of the projection centre

$$[\mathbf{R}^E_C(t)]^T = (\mathbf{R}^E_S(t) \mathbf{R}^S_C)^T = \frac{1}{\omega^2 + a_{(t)}^2 + b_{(t)}^2 + c_{(t)}^2} \begin{bmatrix} \omega^2 + a_{(t)}^2 - b_{(t)}^2 - c_{(t)}^2 & 2a_{(t)}b_{(t)} + 2\omega c_{(t)} & 2xc_{(t)} - 2\omega b_{(t)} \\ 2a_{(t)}b_{(t)} - 2\omega c_{(t)} & \omega^2 - a_{(t)}^2 + b_{(t)}^2 - c_{(t)}^2 & 2b_{(t)}c_{(t)} + 2\omega a_{(t)} \\ 2b_{(t)}c_{(t)} + 2\omega b_{(t)} & 2b_{(t)}c_{(t)} - 2\omega a_{(t)} & \omega^2 - a_{(t)}^2 - b_{(t)}^2 + c_{(t)}^2 \end{bmatrix} \quad (11)$$

at the instant (t) expressed in the ECF coordinate system that may corresponds to a position of a GCP in the image. In this way it can be replaced in expressions (1) above for the position (line j) that corresponds to a time (t).

For any column and row measurement (c, r) of a pixel in the image, the corresponding position of the image point in the detector coordinate system (relative to the centre of the lowest numbered pixel in the detector) is:

$$\begin{aligned} X_D &= 0 \\ Y_D &= -c * \text{detPitch}, \quad \text{with detPitch being the distance (in mm) between centres of adjacent pixels in the array} \end{aligned}$$

To convert these detector coordinates to camera coordinates, it is necessary to apply the rotation and translation given by the following equations:

$$\begin{aligned} X_C &= \cos(\text{detRotAngle}) * X_D - \sin(\text{detRotAngle}) * Y_D + \text{detOriginX} \\ X_C &= \sin(\text{detRotAngle}) * X_D + \cos(\text{detRotAngle}) * Y_D + \text{detOriginY} \dots \dots \dots (7) \\ Z_D &= C \text{ (Virtual Principal Distance)} \end{aligned}$$

With detRotAngle being the Rotation of the detector coordinate system as measured in the camera coordinates system in degrees. detOriginX and detOriginY are the X and Y coordinates of the pixel 0 in the linear detector array, in the camera coordinates system, in mm. detRotAngle, detOriginX and detOriginY are included in the calibration data file (*.geo).

As Level 1B images do not have lens distortion the corrected image point is identical to the measured image point, hence:

$$\begin{aligned} X_C' &= X_C \\ Y_C' &= Y_C \dots \dots \dots (8) \\ Z_C' &= Z_C \end{aligned}$$

The unit vector w_C that is parallel to the external ray in the camera coordinate system is just the position of (X_C', Y_C', Z_C') relative to the perspective centre at (0, 0, 0), normalized by its length. In matrix notation, this vector is:

$$\mathbf{W}_C = (X_C', Y_C', Z_C')^T \quad \text{and} \quad \mathbf{w}_C = \mathbf{W}_C / \|\mathbf{W}_C\| \quad (9)$$

It is possible to convert this vector first to the spacecraft coordinate system and then to the ECF system. The unit quaternion for the attitude of the camera coordinate system, i.e., the quaternion for the rotation of spacecraft frame into the camera frame q^C_S , is in the geometric calibration file (*.geo). Then, using quaternion algebra

$$\begin{aligned} \mathbf{w}_E &= \mathbf{q}^E_S(t)^{-1} \mathbf{q}^S_C^{-1} \mathbf{w}_C \mathbf{q}^S_C \mathbf{q}^E_S(t) \quad \text{or} \\ \mathbf{w}_E &= \mathbf{q}^S_E(t) \mathbf{q}^C_S \mathbf{w}_C (\mathbf{q}^E_S(t) \mathbf{q}^C_S)^{-1} \quad \text{or using matrix algebra,} \\ \mathbf{w}_E &= \mathbf{R}^E_S(t) \mathbf{R}^S_C \mathbf{w}_C \dots \dots \dots (10) \end{aligned}$$

The resulting multiplication matrix $\mathbf{R}^E_C(t)$ has following form:

With:

ω : constant term, being a function of both scalars q^E_S (4) and q^S_C (4)
 $a_{(t)}; b_{(t)}; c_{(t)}$: Are elements of the instantaneous rotation matrix $[\mathbf{R}^E_C(t)]^T$ also function of the quaternions $q^E_S(t)$ for the instant (t) and q^C_S

The above instantaneous matrix rotation can be used in expressions (1) above for the corresponding line (time) image where a CGP or an interest point is to be observed.

3.2 Rational Polynomial Coefficients

The relation of the images to the ground coordinates system can be expressed in form of Rational Polynomial Functions. They describe the scene position as the relation of a polynomial of the three dimensional coordinates divided by another. Strictly speaking the RPC expresses the normalized column and row values in an image (c_n, r_n), as a ratio of polynomials of the normalized geodetic latitude, longitude, and height, (P, L, H). Normalized values are used instead of actual values to minimize the computational errors. The scales and offset of each parameter are selected so that all normalized values fall within the range [-1, 1]. The latitude and longitude values are corresponding with the ellipsoid WGS-84, expressed in decimals of degrees and the height values are WGS-84 ellipsoidal heights expressed in meters. (Grodecki 2001)

4. EXPERIMENTAL TEST

QuickBird Basic Imageries within the area of Phoenix – Arizona and Atlantic City – New Jersey have been oriented. In the area of Phoenix, Digital Orthophoto Quads (DOQQs) of the USGS having a GSD of 1m were 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 1:19,200 and a DEM with accuracy in the range of the 50 cm were used.

Neighbourhood DOQQs are overlapping. In the overlapping area of Phoenix, 112 corresponding points were measured. The Root Mean Square (RMS) difference of coordinates was $\pm 1.43m$ leading to an individual horizontal coordinate accuracy of $\pm 1.01m$ 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 $\pm 0.6m$ standard deviation for X and Y.

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. The view direction is 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, especially the yaw control.

Figure 2 shows the discrepancy vectors after an orientation of a QuickBird Image in the area of Phoenix – Arizona and table 1 contains the results in terms of root mean square discrepancies at GCPs of scenes in the same area and for different number and distribution of GCPs.

In the scene 12450 of the area of Phoenix, 48 points were transferred and measured from the corresponding DOQQs. This was done by manual digitization. Care was taken in trying to pick up symmetric shape features as GCPs. This led to root mean square discrepancies of $RMSX = 1.00m$ and $RMSY = 0.83m$, corresponding to 1.5 pixel – a sufficient but not too good result. The main reason for the limited accuracy is caused by the poor quality of the control points. They are

transferred from USGS DOQQs with interpolated heights using also a 7.5’ USGS DEM. This is not a check for the accuracy possible by the use of QuickBird satellite images, it is more a check of the DOQQs.

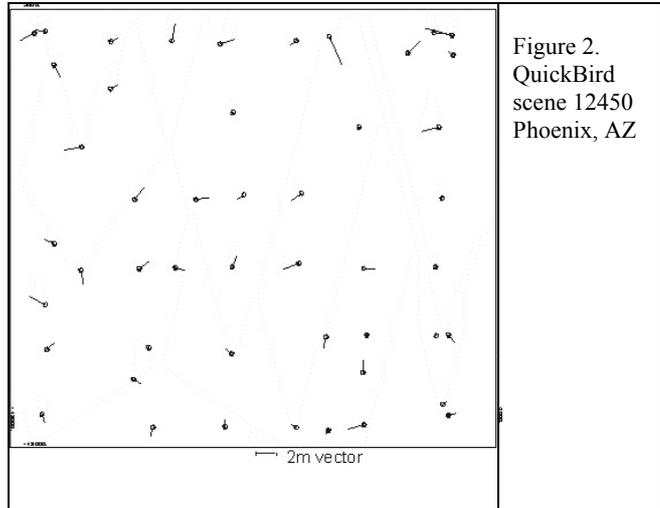


Figure 2. QuickBird scene 12450 Phoenix, AZ

An additional measurement 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 $RMSY = 1.25m$ was achieved. This was similar in the scene 12451. A reduced number of control points (see table 1) has led to satisfactory results at the check points having in mind the fact that neither the GCPs nor the check points are error free.

| Scene | Ground Control Points | | | Check points | |
|-------|-----------------------|----------|-----------|--------------|-----------|
| | 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 1. RMS discrepancies at control & check points. scenes 12450 and 12451, Phoenix - Arizona

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 GCPs 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 manual measurement.

| Type observation | No. GCPs | σ_0 [μm] | GCPs | | Check Points | |
|------------------|----------|---------------------------------|-----------|-----------|--------------|-----------|
| | | | RMS X [m] | RMS Y [m] | RMS X [m] | RMS Y [m] |
| Manu. | 174 | 14.6 | 0.85 | 0.64 | | |
| Autom. | 398 | 11.4 | 0.55 | 0.64 | | |
| Autom. | 25 | 14.1 | 0.49 | 0.74 | 0.69 | 0.72 |
| Autom. | 20 | 13.4 | 0.53 | 0.56 | 0.69 | 1.39 |
| Autom. | 15 | 19.0 | 0.54 | 0.96 | 0.78 | 1.38 |

Table 2. RMS discrepancies at GCPs & check points scene of Atlantic City, New Jersey

The accuracy is reaching approximately 1 pixel, which seems to be the operational result. Nevertheless, it was noticed 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_0) becomes larger (see table 2 above).

As shown in the left hand side of Figure 3, the influence of the yaw control to the scene is covered by the additional parameters. This is reaching an angular affinity in the order of 12.5° . The non linear effect on the right hand side of figure 3 shows the influence of the low attitude frequencies to the scene. These are also being removed by the included additional parameters and tested for over-parameterization based on the statistical procedures explained above. The QuickBird scene of Atlantic City was also bundle adjusted using the ephemeris and the attitude quaternion approach. This was done with the 398 automatically matched and transferred control points from a higher accuracy digital ortho with heights interpolated from a high accurate DTM. The computation was made with the Multi-Sensor-Triangulation Software of Socet Set that includes the QuickBird sensor model. Table 3 shows the arrived results.

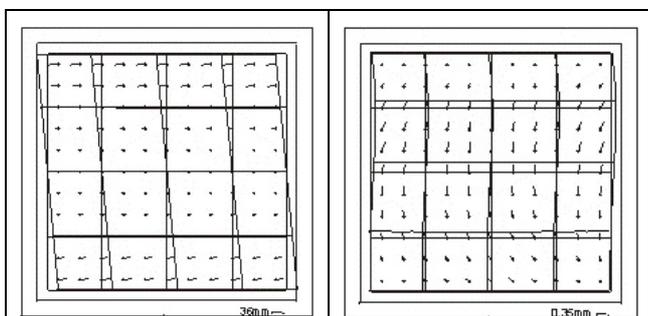


Figure 3. Systematic image errors QuickBird Atlantic City, NJ left: overall effect right: without dominating angular affinity

The results based on the platform ephemeris and the attitude quaternions reported in table 3 first line, is in the same range like the adjustment with BLASPO which is just based on the general orbit information and the view direction. It is difficult

to compare the results directly because of slightly different definition of the RMSX and RMSY.

| | sigma0 | RMSX | RMSY |
|---|-------------|-------|-------|
| Eph. and Quaternions Approach (Socet Set) | 1.1 pixels | 0.58m | 0.48m |
| BLASPO | 0.95 pixels | 0.55m | 0.64m |

Table 3. QuickBird Atlantic City, results of bundle adjustment with 398 control points using the ephemeris and attitude quaternions (Socet Set) and bundle orientation just based on view direction

The Socet Set definition is like following: "Given the original measured image coordinates and the adjusted support data (i.e., adjusted positions of the projection centre along the orbit and instantaneous attitude data), the adjusted imaging ray is defined. Then the point on the adjusted ray nearest the control point is computed. The difference between this computed point and the original measured control coordinates is the error. That means the minimum distance in the space between the original ray and the adjusted ray".

The reported discrepancies at BLASPO are computed as the distance between the intersection point of the adjusted ray and the terrain, and the originally measured Ground Control Point.

5. GENERATION OF ORTHOIMAGES

The geometric 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 DEM. 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.

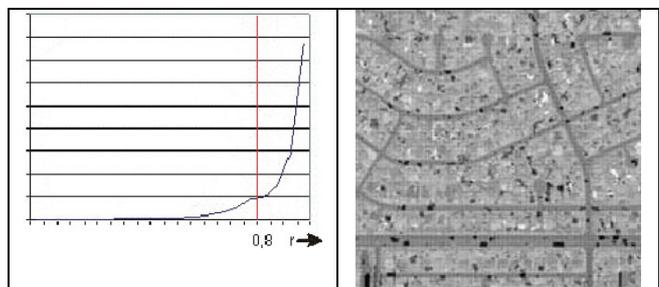


Figure 4: Image matching of QuickBird Images Left: Frequency distribution of Correlation Coefficients Right: sub-image overlaid with matched points (dark=not matched)

From QuickBird, two partially overlapping images taken with 10 days difference in time over the suburbs of Phoenix-Arizona, having a height to the base ratio of only 9.1, have been used for generating a DEM. In the model area, the change of the vegetation and the sun elevation angle were negligible, resulting in good conditions for image matching. The automatic image matching gave excellent results with a vertical accuracy of $\pm 4.8\text{m}$ 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 4). The matching failed only in few limited areas with very low contrast like roads, sandy areas and a few roofs. 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 al 2002).

Allowing for the orientation of the satellite scene no more than one pixel and if no more than two pixels are allowed for the influence of the DEM to the final digital ortho, the required accuracy of the DEM which can be used for the ortho-rectification will depend on the incidence angle of the satellite image. The incidence angle is the nadir angle of the imaging ray at the terrain surface which is larger than the nadir angle at the projection centre, caused by the earth curvature.

| |
|--|
| $SX_{xz} = \sqrt{SX_{ortho}^2 - SX_o^2}$ <p>SX_{xz} = error component allowed as function of S_z SX_{ortho} = standard deviation of orthoimage SX_o = standard deviation of orientation</p> <p>Formula 1: standard deviation acceptable for the influence of the DEM to the horizontal location of orthoimages</p> |
| $SZ_{allowed} = \frac{SX_{xz}}{\tan \eta}$ <p>η = incidence angle of space image</p> <p>Formula 2: acceptable Z-standard deviation of the DEM for the generation of ortho-images</p> |

Table 5: Accuracy requirements of a 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 |
| uncidence angle η | SZ _{allowed} [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 a DEM as a function of the incidence angle for different ortho accuracies

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.

6. CONCLUSIONS

The inner accuracy of the satellite line scanner images from QuickBird are in the sub-pixel range. When the image

orientation is determined using the corresponding rigorous models, under operational conditions, the geometric limitations are not due to the geometric image quality but to the quality and accuracy of the GCPs. This includes the identification of the GCPs in the scenes. Polynomial 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. The orientation just with rational polynomial coefficients has to be improved by control points with a shift, affinity transformation or even an improvement of the nominal collection elevation. To avoid an over parameterization, all computed parameters shall be tested for significance.

Bundle orientations of QuickBird basic imagery based on Space resection with additional parameters for the removal of systematic effects caused by low frequency movements of the platform, gives similar accuracy results than the bundle adjustment based on ephemeris and attitude quaternions.

To avoid over parameterization, adjusted additional parameters shall be tested for statistical significance, numeric stability and internal and external reliability and the not justified values have to be excluded from the computation. This can be based on above mentioned statistical tests.

DEMs can be generated with high resolution space imagery by automatic image matching. If the stereo-images are taken within the same orbit or with short time interval, the correlation quality is quite better like with analogue aerial photographs. The digital space images are not affected by film grain and do have most often a better radiometric quality.

Given the accuracy specification of the final digital ortho, the required accuracy of the DEM to be used for the ortho-rectification is inversely proportional to the tangent of the incidence angle.

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