

A Quaternion based Rigorous sensor model for Quickbird with only one Ground Control point

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Abstract

The basic image product of Quickbird PAN data contains information about satellite position, velocity and orientation information together with interior orientation parameters. The model utilizes this information and one precise ground control point to achieve root mean square error of better than one meter in both directions. The paper presents description of model, Quickbird PAN payload geometry, comparison of model derived results with Rational polynomial coefficients derived results. The model can be used operationally and can also be used to derive other products such as standard and ortho products

Introduction

The Quickbird satellite was successfully launched from Vandenburg air force base, California on October 18,2001. The satellite is orbiting at 450 km altitude in a sun-synchronous orbit. It is a three axes stabilized small satellite weighing about 1000 kg. It is equipped with a star tracker, inertial reference unit, reaction wheels and a C/A code GPS receiver besides other high precision instruments to provide precise orbit, attitude measurement and control. The satellite has 61-72 cm resolution panchromatic and 2.44-2.88 m resolution multi-spectral sensor. In addition Quickbird has along – track/ across-track stereo acquisition capability. Launch of Quickbird has narrowed down the gap between the satellite image and aerial image for many photogrammetric, remote sensing and mapping applications. Quickbird supplies three different types of products, namely basic, standard and ortho- imagery.

In last four years, the researchers worldwide reported a good amount of work using Quickbird data. It is indeed established that Quickbird data is in compliance with the claimed geometric accuracy standards for all types of products (Ref Nouguchi)

For any satellite/ aerial image, it is important to establish the image – object relation and refine the model using a few ground control points and tie points. This process is known as geometric modeling. The overall geometric accuracy depends on the accuracy of the modeling. Geometric accuracy requirements may vary depending upon the application. For example, it can be very stringent in case of large-scale mapping and photogrammetric applications, while in case of reconnaissance and asset monitoring, damage assessment or similar applications, absolute metric accuracies are not critical but the image must not contain large relative distortions. Geometric accuracy can be further categorized as

- (i) Absolute geometric accuracy
- (ii) Relative geometric accuracy

There are many techniques to establish and model the image –object relation. In recent past rational function model (RFM) have been very popular due to their sensor independent characteristics, simple implementation techniques and acceptable achievable accuracies. However, there has been constant debate over the use of rational function model instead of a physical sensor model. A further discussion on this topic is presented in this paper.

Theoretically, it is accepted that a suitable rigorous physical sensor model is capable of providing best geometrical accuracies over any other models (Ref Volpe et al). Rigorous physical sensor model are robust, generic in nature and the requirement on number of ground control points are less. These models work well with a scene or larger image strips. For Quickbird images, Toutin developed a rigorous sensor model; the model is implemented with a COTS package. It requires a minimum of six precise ground control points. It is an adoption of Toutin's generic model, which is used for many other satellites.

The main objectives of the paper are

1. To develop a rigorous physical sensor model for Quickbird with a minimum number of control points for operational use. The model should be robust and not sensitive to GCP distribution.
2. Minimize the mathematical complexities of the model without compromising on achievable accuracy.
3. Compared the model-derived results with rational function model derived results.

Quickbird follows an open system. Image support data files with basic image/stereo pair contain information about the interior orientation parameters, position, velocity and orientation information at specified interval. The basic image/ stereo pair are corrected only for scan variation related distortions and internal sensor geometry besides radiometric correction. The orientation parameters and camera bias parameters are provided as quaternion To image a particular area of interest, a series of rotations have to be performed. It is difficult to follow and provide the exact orientation sequence in terms of traditional Euler angle representation (large angle successive rotations do not commute). Use of quaternion simplifies the mathematical formulation and saves computational time. Onboard navigation is generally done using quaternion. With proper blunder removal and bias adjustment, these onboard quaternion values provide best information about the orientation of the satellite, which if correctly used is likely to represent real behavior of satellite very closely.

The developed model has used the satellite position, velocity and orientation information together with interior orientation parameters to establish object and image space relation. **The achieved accuracy with one precise ground control point is better than one meter (RMS) in both the direction.** If no control point is used the absolute accuracy is 18 m rms and the relative accuracy is better than a meter. While if Quickbird supplied Rational Polynomial coefficients (RPC) are used to establish image object relation, absolute accuracy is within 20 meter but relative accuracy is poor (about 12 m)

The paper presents brief description about Quickbird data products, discussion on various modeling techniques. These are followed by description of Quickbird payload geometry and model, result, analysis and conclusion.

Types of Product

Digital globe provides Quickbird data in three different product types (Ref: digitalglobe website)

Basic imagery is the least processed of the Quickbird product suit and is corrected for radiometric distortions, internal sensor geometry, optical distortions and sensor distortions.

Standard Imagery is a geo-referenced product, which is radiometrically calibrated, corrected for sensor and platform induced distortions, and mapped to a cartographic projection.

Ortho-imagery is a terrain corrected product, which is radiometrically, calibrated, corrected for sensor and platform induced distortions, and mapped to a cartographic projection. This product is GIS ready and can be used as image base map for a wide variety of applications, where a high degree of absolute accuracy is required.

Different Modeling Techniques

A “model” is an object or concept, which is used to represent something else. It is reality scaled down and converted to a form, which we can comprehend.

The sensor models are classified as physical models, abstract models and generalized models. Choice of a particular type depends upon the performance and application requirements, quality and availability of input control and sensor information, economics and practicalities of obtaining additional information. If camera calibration or orientation information is available, then a physical model is the logical choice to take full advantage of it.

Rational polynomial coefficients are one of the generalized models representing the transformation between object and image space as the ratio of polynomial functions (Ref: Tao).

Rational polynomial coefficients can be determined by two approaches. First approach is termed as terrain independent scenario; the rational function model performs as a fitting function between the image grid and the object grid. The RFM defined this way is proved to be capable of achieving a very high accuracy to original physical sensor model. In this approach the RFM can be considered as ‘model of model’. Imagery vendors generally adopt this approach to generate rational polynomial coefficients. However, it may not be guaranteed to always approximate the real imaging process well. The requirement for control information may not be met satisfactorily, or ground control information is not available while determining the physical sensor model itself. Often user is requested to provide precise GCP and DEM to get high precision products. This presents a problem for users who are prohibited to release topographic data.

It is possible to refine rational function model either in image or ground space using one or more precise ground control point. The major disadvantages of RFMs are inability to model local distortions such as high frequency variation, limitation on the image size, difficulty in representing asynchronous mode of imaging To improve the ability to model local distortions RFM should be applied to geo-referenced data with systematic distortions corrected. Work of some researchers show that it is not always possible to acquire the best possible accuracy with RFM (Petrie 2002). Even in our experiment we observed a random error of 15 m on independent control points using the rational polynomial coefficients provided by Quickbird. However only a systematic error of 12 m was observed when the developed rigorous sensor model is used without using any GCP. This systematic bias was removed using one ground control point and an absolute accuracy of better than 1m was obtained for Quickbird PAN data. . Second approach is termed as terrain dependent approach; the RFM tries to approximate the imaging geometry using a large number of well-distributed precise ground control points. In this context RFM behaves as rubber-sheeting model. There are many experiments carried on using frame, pushbroom or SAR images to asses the approximating ability of RFM

obtained in this manner, and the accuracy is high provided that a large number (for instance, as twice as the minimum number of GCPs are required to obtain a closed form solution) of evenly distributed GCPs across the scene. Nevertheless, the terrain dependent approach may not provide a sufficiently accurate and robust solution if the above requirements for control information is not satisfied. Therefore, the RFM solved by terrain dependent approach may not be used if high accuracy is required.

If image size is larger, then it needs to be divided in sub-images and rational polynomial coefficient for each image has to be calculated. The number of required ground control points increases proportionally. It is difficult to meet all such requirements in an operational scenario.

Merits of physical sensor models have attracted many researchers and photogrammetric and GIS s/w development agencies to develop and implement rigorous sensor model for Quickbird. An absolute accuracy of less than 2 m is reported by using the physical sensor model and six precise ground control points (Ref Toutin). Toutin's model is implemented with a commercial s/w package. The mathematical complexity of this model is high and a minimum of 6 control points is required. Similarly some other s/w packages utilize sensor orientation and ephemeris information of QuickBird data to establish image-object relation. However mathematical and functional details, accuracy and required no of GCPs are not available.

The mathematical formulation of our model is relatively less complex, only one control point is required to improve the absolute accuracy and speed of computation is comparable to computation through RFM.

Quickbird PAN Payload Geometry

The Quickbird sensor contains six detector chip assemblies for each collected band. There are 27552 panchromatic detectors in the combined detector chip assembly of PAN sensor. The basic image is corrected for the sensor geometry and the image line can be considered as imaged from a virtual array. The Quickbird field of view is 2 degree, which creates a swath width of 16.5 km. Figure 1 shows the detector chip assembly of PAN sensor.

Description of the model

The geometric distortions associated with each image acquisition system are unique. However, it is possible to enumerate some common sources of geometric distortions for spaceborne pushbroom line scanner images in visible part of the spectrum.

These are

1. Change of perspective center for each imaged line
2. Change in orientation of the spacecraft
3. Change in platform velocity and altitude.
4. Rotation of earth
5. Mode of imaging
 - Synchronous
 - Asynchronous
 - Time delay integration (TDI)
6. Calibration of interior orientation parameters of optical system and determination of camera bias angles
7. Payload geometry
8. Atmospheric refraction and turbulence

9. Approximating the shape of earth with a mathematical surface

Present era high-resolution satellites have very precise and accurate control and measurement system. The accuracy specification of the onboard control and measurement system are governed by the geometric resolution, SNR, imaging technique and geometric accuracy specification.

Quickbird is a highly agile satellite with single camera system. It can acquire stereo images as along-track or across-track stereo pair. In short, a series of maneuvers are common for Quickbird to acquire images.

Traditionally, photogrammetrists have been using Euler angles (roll, pitch, yaw) to represent the orientation of the spacecraft as rotations with respect to the reference frame. However, when rotation angles are large and many combinations of rotations are involved, it becomes important to know the exact sequence of rotations and clear definition of rotation axes (large angle successive rotations do not commute). There are alternative ways to provide orientation information, such as Euler axis/angle, Gibbs vector or Euler symmetric parameters. Euler 's symmetric parameters are also known as Quaternion. Euler angle representation shows singularities at some angles and involves trigonometric function, while quaternion representation does not have such limitations. Quaternions are generally used for inertial navigation of the spacecraft. The navigation and control information is sent to ground as onboard quaternion, which after certain level of processing is most accurate and reliable information about the spacecraft orientation during imaging.

Quickbird PAN data is collected in time delay integration (TDI) mode. A TDI technique requires that each stage see exactly same area of earth, which has been seen by previous stages. Although the time lag between the two stages is very less, a very high-resolution sensor (60 cm) does not see the same point due to earth rotation. Therefore the satellite has to be rotated about Z_s axis to compensate for earth rotation. This rotation is very small, but it must be accounted in sensor model. These angular rotations are part of orientation and available as quaternion.

Quickbird basic images are corrected for scan rate variation and internal sensor geometry besides radiometric correction. Thus it is not needed to include these factors in the physical sensor model. The position and velocity information is provided at every 0.2-second interval for imaging duration. This information is in ECEF co-ordinate system, and is generated with refined orbit parameters. The attitude information is provided as quaternion with respect to ECEF. Since ECEF is used as reference co-ordinate system, the earth rotation component is already accounted. The quaternion connecting spacecraft co-ordinate system to camera co-ordinate system is also available and these are presumably generated after estimation of camera biases. The two successive rotations from ECEF to spacecraft co-ordinate system, and spacecraft to camera co-ordinate system transforms the co-ordinate of the ground point in camera co-ordinate system at the particular instant t . Similarly the perspective center co-ordinates are also transformed to camera co-ordinate system. The origin of detector co-ordinate system w. r. to camera co-ordinate system is available as internal orientation parameter. The atmospheric corrections are a bias for the scene size and are incorporated using Noerdlinger's model. The photogrammetric model is based on collinearity condition. Quaternions are used to formulate transformation matrix. The imaging time for a given object point is found by a method described by Mahapatra et. al. . Once imaging time is known, it can be converted

to line number using the scene start time and line integration time. A block diagram of important blocks to compute image space co-ordinate for given object space co-ordinate is shown in figure (2).

Description of the data set

Quickbird acquired PAN and multi-spectral stereo pair of part of Hyderabad, India on 16-Jan-2004. It is a stereo-1B data with only radiometric and internal sensor geometry related corrections. Each scene covers approximately 396 sq km area. The nominal resolution is 0.6 meter for PAN and 2.4 meter for multispectral data. The along-track stereo pairs are obtained with +28 and -28 deg off-nadir viewing angles providing a B/H ratio of 1.2. The data is almost cloud free. Ten GPS surveyed ground control points with accuracies better than 25 cm are identified on Quickbird images. These GCPs are located at building corners. The terrain undulation in this area is approximately 200 meters.

Result and Analysis

The result presented here are for Quickbird Pan Camera. The two stereo images are acquired at approximately 50-second interval. Here two images are handled as two separate images to assess the geometric fidelity of the camera. No attempt is made to use tie points between images to determine relative orientation of the camera at two instants. Thus two stereo images can be considered as two test data scenes. The GPS surveyed ground control points are identified in both images. The horizontal datum for these points is WGS-84 and vertical datum is Ellipsoid. Here any datum transformation is not required.

For known ground co-ordinate, image co-ordinates are predicted using system level information. The difference between actual and estimated image position is multiplied by resolution of Pan sensor. Table 1 shows the difference between actual and estimated image co-ordinates at each independent control point in meters. For Quickbird PAN-01 image the difference along track as well as in across track direction is a bias. The average error is 18.05 m and 7.44 meters respectively. These represent the overall absolute accuracy achievable through model using the system level information. The significant part is very low standard deviation in both the direction, which is 0.78 m and 0.32 meters. The bias is removed using one ground control point. Results are shown in Table-3. Now RMS error is 0.97 m and 0.50 m in along and across track direction respectively.

Similarly for the PAN-02 data set, the average error in along and across track direction is 16.05 m and -14.25 m respectively if only system level information is used. After removing this bias with one ground control point, the RMS error is 0.95 meter and 1.00 meter respectively.

Quickbird has supplied a set of rational polynomial coefficient to relate object space co-ordinate to image space co-ordinate. For a known ground co-ordinate, the image co-ordinate is estimated using these RFCs. Table -2 shows the difference in actual and estimated residual at same independent control points. It is clear that the difference is not a bias, and cannot be modeled using one or two ground control points. The standard deviation is high, 12.43 m and 11.22 meters for PAN-01 and 12.37 meter and 9.63 meters for PAN-02. It means that although the absolute accuracy using the RFCs meets the specifications, the relative accuracy is not so good. The derived products generated through RFCs will not meet the stringent requirement for large-scale mapping. **While if**

the rigorous sensor model with one very precise ground control point is used, the RMS error is within one meter for both directions. The derived product, such as orthoimage generated using the model is suitable for making 1:5000 scale map.

Conclusion:

The developed model is using only one ground control point to achieve accuracies suitable for 1:5000 mapping. Achieved relative accuracies are significantly superior to the accuracies achieved with vendor supplied rational polynomial coefficients. The model establishes the object-image relation, which can be used to derive other products such as standard product or orthoimages (if suitable DEM is available). The cost of generating these products at user end is comparatively less compared to the vendor provided derived products.

References:

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9. <http://www.digitalglobe.com>

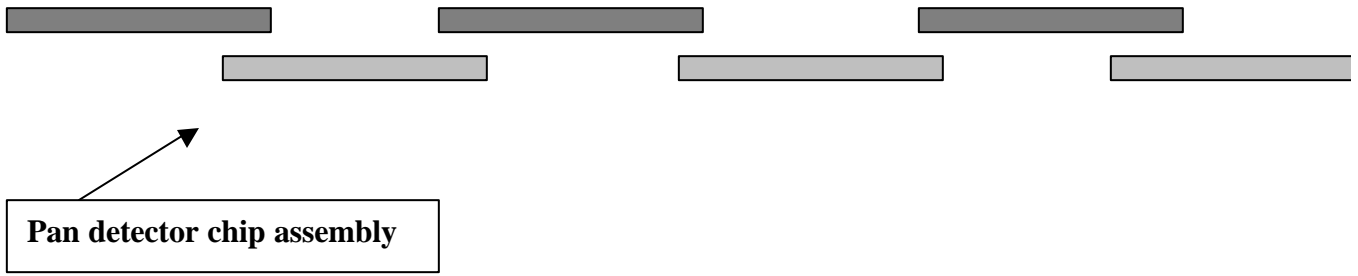


Figure 1: Quickbird PAN detector assembly

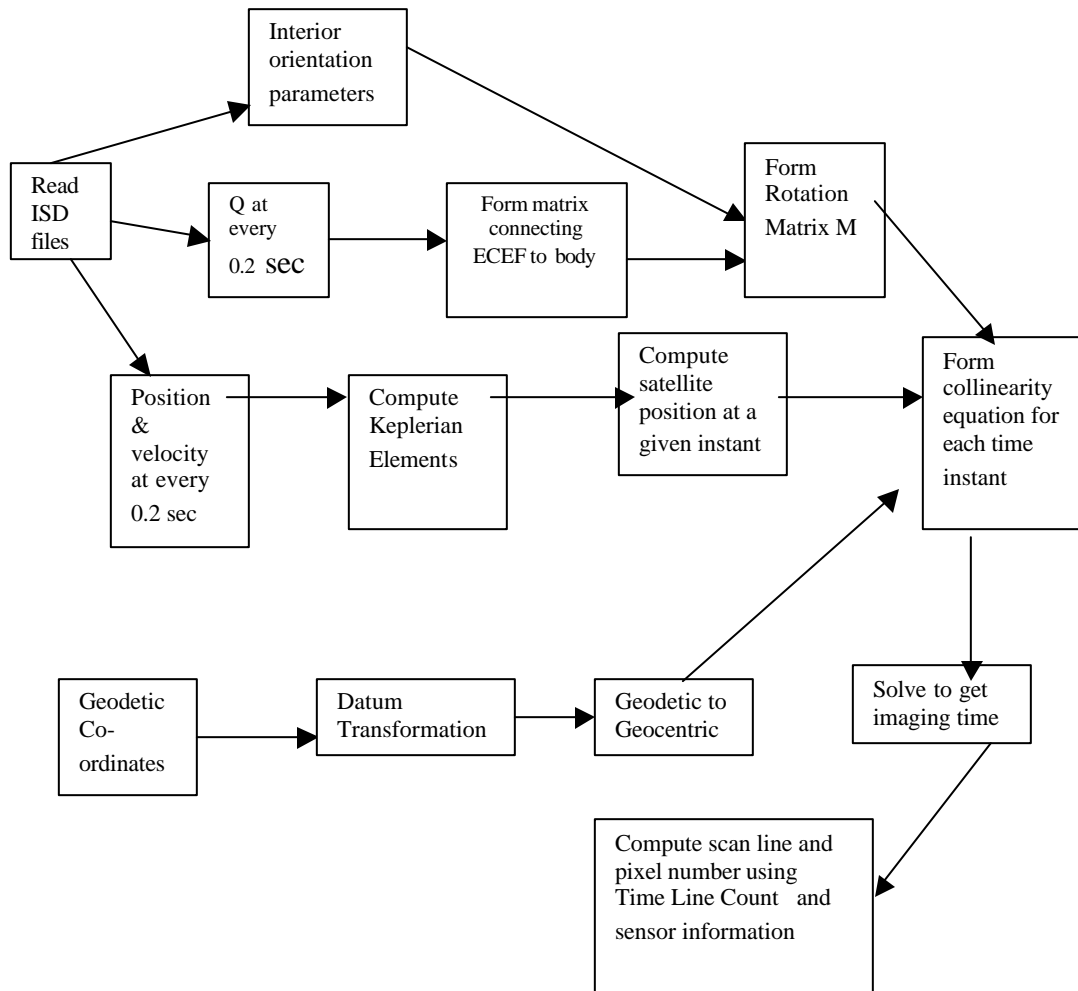


Fig 2: Block diagram of rigorous photogrammetric model relating object and image space

Table 1
Difference between Actual and estimated image position at independent control points using the developed rigorous sensor model (without using any ground control point)

Point no	Quickbird PAN 01		Quickbird PAN 02	
	Difference in along track direction (meters)	Difference in across track direction (meters)	Difference in along track direction (meters)	Difference in across track direction (meters)
1	-17.89	-7.01	-14.92	14.71
2	-17.29	-7.88	-16.31	14.30
3	-17.54	-7.52	-15.89	13.93
4	-19.89	-7.39	-15.67	13.60
5	-18.79	-7.07	-16.27	14.62
6	-18.55	-7.07	-16.73	14.95
7	-17.06	-7.66	-15.84	13.55
8	-17.84	-7.18	-15.80	15.51
9	-17.87	-7.44	-15.81	13.56
10	-17.79	-7.95	-17.25	13.75
Std dev	0.78 meters	0.32 meters	0.60 meters	0.64 meters
Avg	18.05 meters	7.44 meters	16.05 meters	-14.25 meters

Table 2
Difference between Actual and estimated image position at Independent control points using the RFC supplied by Quickbird (without using any ground control point)

Point no	Quickbird PAN 01		Quickbird PAN 02	
	Difference in along track direction in meters	Difference in across track direction in meters	Difference in along track direction in meters	Difference in across track direction in meters
1	-19.01	-12.82	8.40	2.21
2	5.00	-25.30	-13.50	10.19
3	6.07	-27.67	-13.34	8.79
4	20.98	-44.75	-26.94	10.37
5	-6.50	-12.14	-8.25	11.70
6	-2.64	-15.33	-11.38	12.75
7	-4.75	-11.83	-8.21	11.47
8	-7.38	-9.97	-5.69	12.33
9	-12.80	-9.25	-0.43	6.85
10	-24.46	-5.64	8.69	2.16
Std dev	12.43 meters	11.22 meters	10.15 meters	3.73 meters
Avg	-4.5 meters	-17.47 meters	-7.06 meters	8.88 meters
RMS	13.2 meters	20.77 meters	12.37 meters	9.63 meters

Table 3
Difference between Actual and estimated image position at independent control points using the developed rigorous sensor model (using only ONE ground control point)

Point no	Quickbird PAN 01		Quickbird PAN 02	
	Difference in along track direction in meters	Difference in across track direction in meters	Difference in along track direction in meters	Difference in across track direction in meters
1	0.65	0.05	1.80	-0.23
2	1.25	-0.81	0.41	-0.64
3	1.00	-0.45	0.84	-1.01
4	-1.34	-0.32	1.05	-1.34
5	-0.24	-0.007	0.45	-0.32
7	1.48	-0.59	0.88	-1.39
8	0.70	-0.11	0.92	0.56
9	0.67	-0.37	0.91	-1.38
10	0.75	-0.88	-0.52	-1.19
Average	-0.55 meters	0.39 meters	-0.75 meters	0.77 meters
Std_dev	0.80 meters	0.31 meters	0.58 meters	0.63 meters
RMS	0.97 meters	0.50 meters	0.95meters	1.00 meters