IKONOS GEOMETRIC ACCURACY

J. Grodecki and G. Dial
Space Imaging
12076 Grant Street, Thornton, CO 80241, U.S.A.
jgrodecki@spaceimaging.com
gdial@spaceimaging.com

ABSTRACT

IKONOS, the world's first commercial high-resolution imaging satellite, was successfully launched in September of 1999. From a 680 km sun synchronous orbit, the IKONOS satellite simultaneously collects 1-meter panchromatic and 4-meter multispectral images in 4 bands with 11-bit resolution. Interior and exterior orientation are derived from a sophisticated attitude and ephemeris determination systems, a stable optical assembly, and a solid state focal plane. These features make IKONOS ideally suited for high accuracy mapping applications. The paper describes the IKONOS imaging geometry, sensor model, and the geometric accuracy of IKONOS ortho and stereo products.

INTRODUCTION

Since its launch in September of 1999 IKONOS has been collecting high-resolution images over the entire globe. As shown in this paper the IKONOS images exhibit not only high spatial and radiometric resolution but are also highly accurate in the geometric sense.

SENSOR CHARCTERISTICS

Orbital Geometry

IKONOS circles the earth every 98 minutes at an altitude of 680 km in a sun-synchronous orbit with descending node crossing at about 10:30 am local solar time. The orbital inclination is 98 degrees.

Agility

Unlike Landsat, which only images at nadir, and Spot, which can only roll side-to-side for image acquisition, the IKONOS satellite is agile in that it can be rotated to any angle to acquire an image to the side, forward, or aft of the satellite position.

Exterior Orientation (Attitude and Ephemeris)

The satellite ephemeris is determined from the on-board GPS data, post-processed on the ground with a software incorporating sophisticated filtering / orbital modeling algorithms. The satellite attitude is measured by on-board star trackers and gyroscopes. Post-processing the attitude data in a Kalman smoother results in optimal combination of lower frequency star tracker information exhibiting high absolute accuracy with high frequency gyro data being very accurate over short time interval. The relationship between the satellite attitude coordinate system and the IKONOS camera coordinate system is described by the interlock angles. The initial interlock angles were determined by pre-launch assembly measurements and later refined by in-flight calibration.

Interior Orientation

The interior orientation of the IKONOS camera is described by the Field Angle Map (FAM). The Field Angle Map comprises both the optical distortion parameters and the focal plane array layout. The IKONOS solid state focal plane array consists of multiple panchromatic and multispectral line arrays. The Field Angle Map allows one to determine the line-of-sight vector in the camera coordinate system for each image pixel.

Combining satellite attitude, interlock angles, and the Field Angle Map allows calculation of the pointing direction of every image pixel.

Spectral Resolution

IKONOS collects imagery in four multispectral bands and a single panchromatic band. The IKONOS multispectral bands approximate LANDSAT bands 1 through 4. The relative spectral responsitivity for all five bands is given in Figure 1. Conversion of image DN values to absolute radiance, required for remote sensing analysis, can be accomplished with the radiometric calibration coefficients given in [Space Imaging, 2001].

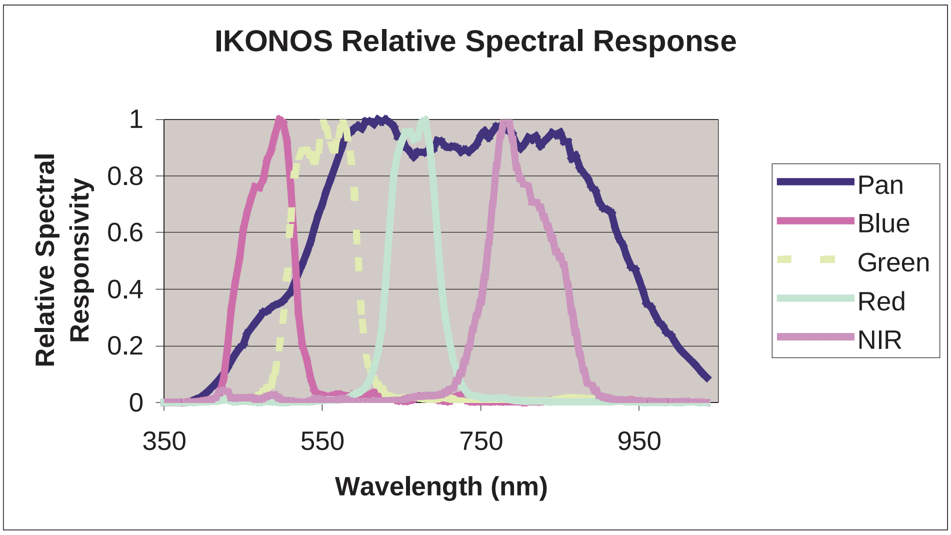


Figure 1. IKONOS Spectral Response Curves.

Radiometric Resolution

Both the panchromatic and all four multispectral bands have 11-bit dynamic range. With 11-bit resolution, details in shadows, highlights, and low contrast scenes can be more easily discerned than in 8-bit images.

Spatial Resolution

The ground sampling distance (GSD) of the IKONOS sensor is 0.82 m (at nadir) for panchromatic images, and 3.28 m (at nadir) for multispectral images. At 30 degrees off nadir the GSD is 1 m for panchromatic and 4 m for multispectral images. Nominal swath width at 1 m GSD is 13 km. All currently offered commercial IKONOS image products are resampled to 1 m GSD, either map projected or epipolar projected. As the width of the Point Spread Function of the IKONOS camera determined mostly by the diffraction limit of the telescope aperture is about 1 m, this does not result in a significant loss of spatial resolution of the final image products.

Temporal Resolution

At 40 degrees latitude the revisit time is 2.9 days at 1 m GSD and 1.5 days at 1.5 m GSD. The revisit times are shorter for higher latitudes and longer for latitudes closer to the equator.

IMAGE COLLECTION

Image Acquisition Geometry

Approximate image acquisition geometry is described by the sensor azimuth and elevation angles contained within the metadata (see Table 1).

Table 1. Sample Image Metadata

```
Acquired Nominal GSD
   Cross Scan: 0.84 meters
   Along Scan: 0.83 meters
Scan Direction: 0 degrees
Nominal Collection Azimuth: 93.7818 degrees
Nominal Collection Elevation: 81.18989 degrees
Sun Angle Azimuth: 151.5820 degrees
Sun Angle Elevation: 29.57948 degrees
```

As shown in Figure 2 below the projection of the line of sight from target to the satellite onto the horizontal plane at the target location defines the sensor azimuth. The sensor azimuth is measured clockwise from the North. The sensor elevation angle is the angle from the horizon up to the satellite.

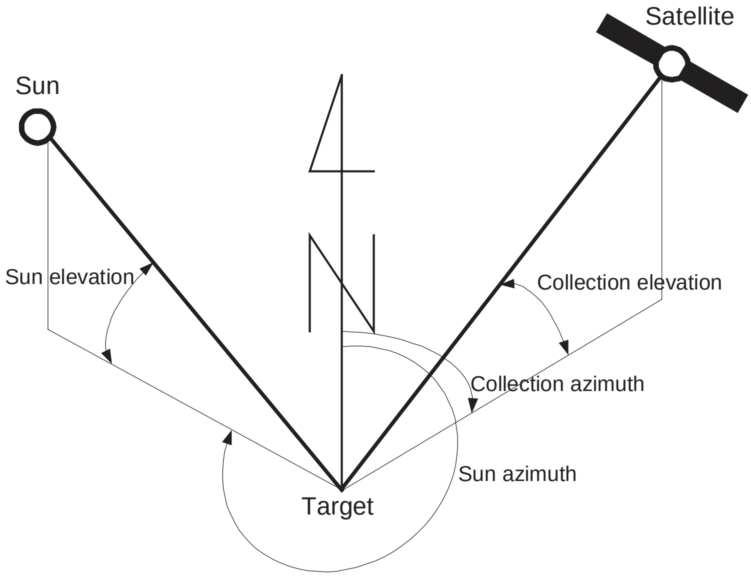


Figure 2. Image Acquisition Geometry

It should be noted that both the sensor azimuth and the sensor elevation angles are not constant for a given image strip and as such should not be used for orthorectification or other geometric corrections. Their accuracy is however sufficient for remote sensing analysis purposes such as topographic normalization.

Mono Collection Geometry

IKONOS mono image strip length typically varies from 10 km to some 200 km. The actual strip length is dictated by the AOI shape and dimensions, weather conditions, collection elevation angle constraints and image scheduling and tasking. Even though in principle IKONOS can collect images at any scan azimuth – as illustrated in Figure 3 – most images are collected in the N-S scan direction. This simplifies collection scheduling and the logistics of the subsequent block adjustment of multiple overlapping images.

Stereo

Unlike e.g. Spot, which takes cross-track stereo images from different orbital passes, IKONOS collects same pass stereo pairs. That is the two images constituting the stereo pair are taken on the same orbital pass. As the satellite approaches the target it yaws, rolls and pitches, as required, to collect the first leg of the stereo pair while pointing in a forward direction. A hundred or so seconds later, after the first image is collected the satellite is maneuvered to again image the same area, this time pointing in a backwards direction. Stereo imaging principle is illustrated in Figure 3 below. Same pass stereo pairs are advantageous for subsequent processing such as feature extraction because the scene content and lighting conditions are virtually the same for the two images.

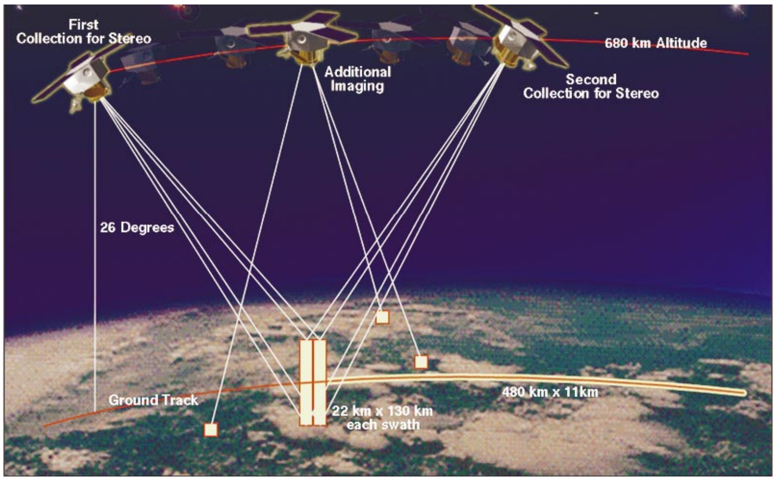


Figure 3. Stereo Image Collection

IMAGE PRODUCTS

Block Adjustment

In order to improve accuracy, multiple overlapping images are block adjusted together. Block adjustment of multiple overlapping images uses least-squares estimation process to estimate the camera model parameters for each image. The images are tied together by tie points whose image coordinates are measured on multiple images. Block adjustment of multiple images without GCP results in minimization of random errors and averaging out of biases affecting geometric accuracy of a single image strip. The ground control, if available, helps to remove the bias errors. Unlike the aerial blocks, the overlap requirement for IKONOS mono or stereo image strips is only about 10%. This is illustrated in Figure 4 below.

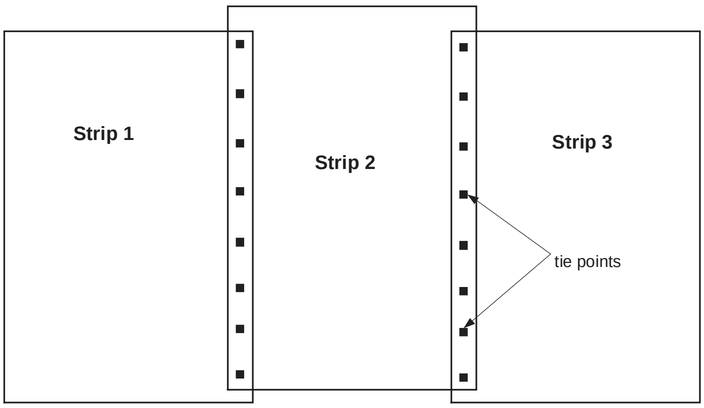


Figure 4. Block Adjustment.

Georectification

Level 2 and Level 3 mono products are georectified, i.e. projected along the line of sight to an inflated ellipsoid, map projected, and resampled to 1 m GSD. Level 2 mono (Geo) and Standard Stereo products are processed without ground control. Level 3 mono and Precision Stereo products are processed with ground control. Georectification is shown conceptually in Figure 5.

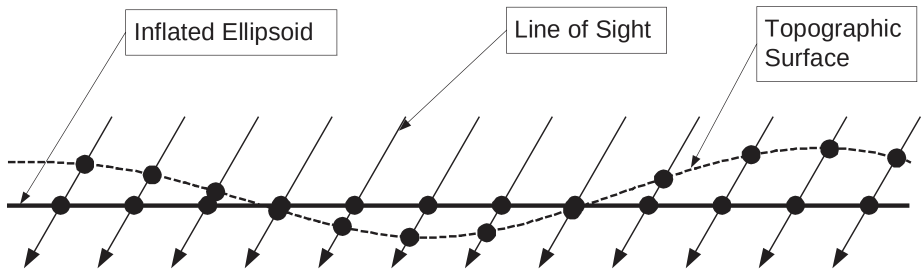


Figure 5. Georectification Process.

Since no terrain model is used in the georectification process, the resulting images are not corrected for terrain displacement. Thus, the horizontal accuracy of a georectified product is determined by both the satellite attitude and ephemeris (and GCP in the case of Level 3) and the terrain displacement. Since the terrain-induced displacement can reach hundreds of meters, the georectified products are not suitable for mapping applications. Accuracy of the Level 2 Geo products is specified as 50m CE90 exclusive of terrain displacement (see Table 2). As demonstrated in this paper the geometric accuracy of the IKONOS satellite without ground control is actually much better than 50m CE90.

Table 2. Georectified Products

Level	Description	Rectification	Accuracy	Mosaic (Level 7)	GCP
2 mono	Geo	Inflated ellipsoid	50m CE90+ terrain displacement	Not recommended (due to shear)	No
3 mono	Adjusted w/ GCPs and georectified	Inflated ellipsoid	2m CE90 + terrain displacement	Not recommended (due to shear)	Yes

Orthorectification

Orthorectification removes distortions in the imagery due to topography. The result is a map accurate product that can be used in GIS and other mapping applications. Depending on the collection geometry, availability of GCPs, and type and accuracy of a DEM used for orthorectification, Space Imaging offers four levels of accuracy for the orthorectified products (see Table 3).

Table 3. Orthorectified Products

Level	Description	Rectification	Accuracy	Mosaic (Level 7)	GCP
4a	Reference	Orthorectified	25m CE90	Yes	No
4a	Pro	Orthorectified	10m CE90	Yes	No
4b	Precision	Orthorectified	4m CE90	Yes	Yes
4b	Precision Plus	Orthorectified	2m CE90	Yes	Yes

Epipolar Resampling

To facilitate working with stereo imagery IKONOS stereo products can be resampled to epipolar geometry. For pushbroom sensors the epipolar geometry deviates from the well-known epipolar geometry of a frame camera. The epipolar lines for pushbroom images are no longer straight lines but complex curves instead. It turns out that, however, over a limited extent straight lines can accurately approximate IKONOS epipolar geometry. Thus, the IKONOS stereo images are divided into segments whose size is dictated by the requirement to minimize epipolar resampling errors.

Table 4. Stereo Products

Level	Description	Projection	Accuracy	Mosaic (Level 7)	GCP
2 stereo	Standard stereo	Epipolar or Map	25m CE90 22m LE90	No – cannot mosaic stereo.	No
3 stereo	Precision Stereo	Epipolar or Map	2m CE90 3m LE90	No – cannot mosaic stereo.	Yes

CAMERA MODEL

In general, a camera model relates object coordinates to image coordinates. Physical camera models are based on the interior and the exterior geometry and other physical properties of the sensor. For 1-meter GSD pushbroom sensors like IKONOS fully parametrized camera models are extremely complex making them enormously difficult to implement. For example the IKONOS System Geometric and Mathematical Model document consists of 183 pages while the accompanying interface control document for the thousands of data items used in the IKONOS camera model is 225 pages. To simplify interface with the end users of IKONOS imagery, Space Imaging uses the Rational Polynomial Camera (RPC) model, also called an Image Geometry Model (IGM),in lieu of the physical IKONOS sensor model to communicate the imaging geometry. RPCs are being distributed with all stereo images and the so called Geo Ortho Kit images. Geo Ortho-Kit images are acquired with a high elevation angle, georectified, and produced with RPC data. As shown in subsequent sections, while being mathematically simple and thus easy to implement, the IKONOS RPC model maintains full accuracy of the physical IKONOS camera model.

Physical Camera Model

For an image taken with a pushbroom camera each image line is taken at a different instance of time (see Figure 6). The exterior orientation parameters, i.e. the attitude angles (roll(t), pitch(t) and yaw(t)) and the position of the perspective center (PC(t)) change from scan line to scan line. The interior orientation parameters, which comprise the focal length, the principal point location, the lens distortion coefficients, and other parameters directly related to the physical design of the sensor, are in general the same for the entire image. A generic pushbroom camera model can be expressed by modified collinearity equations in which all exterior orientation parameters are defined as a function of time (see e.g. [Mikhail et al., 2001]).

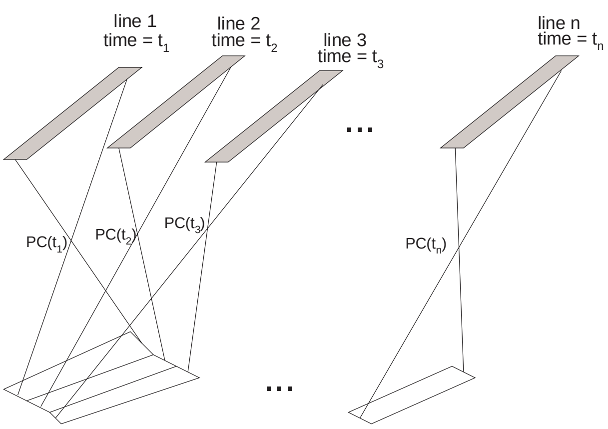


Figure 6. Pushbroom Camera

Rational Polynomial Camera Model

The IKONOS RPC model provides a functional relationship from the object space to the image space. The RPC functional model is of the form of a ratio of two cubic functions of the object space coordinates [Grodecki, 2001]. Separate rational functions are used to express the relationship of the object space to line, and the object space to sample coordinate. The line RPC model is given as

$$l = \frac{Num_L(U,V,W)}{Den_L(U,V,W)},$$

$$\begin{aligned} Num_L(U,V,W) = {} & a_1 + a_2 \cdot V + a_3 \cdot U + a_4 \cdot W + a_5 \cdot V \cdot U + a_6 \cdot V \cdot W + a_7 \cdot U \cdot W + a_8 \cdot V^2 + a_9 \cdot U^2 \\ & + a_{10} \cdot W^2 + a_{11} U \cdot V \cdot W + a_{12} \cdot V^3 + a_{13} \cdot V \cdot U^2 + a_{14} \cdot V \cdot W^2 + a_{15} \cdot V^2 \cdot U + a_{16} \cdot U^3 + a_{17} \cdot U \cdot W^2 \\ & + a_{18} \cdot V^2 \cdot W + a_{19} \cdot U^2 \cdot W + a_{20} \cdot W^3 \end{aligned}$$ and

$$Den_L(U,V,W) = b_1 + b_2 \cdot V + b_3 \cdot U + b_4 \cdot W + b_5 \cdot V \cdot U + b_6 \cdot V \cdot W + b_7 \cdot U \cdot W + b_8 \cdot V^2 + b_9 \cdot U^2$$
$$+ b_{10} \cdot W^2 + b_{11} U \cdot V \cdot W + b_{12} \cdot V^3 + b_{13} \cdot V \cdot U^2 + b_{14} \cdot V \cdot W^2 + b_{15} \cdot V^2 \cdot U + b_{16} \cdot U^3 + b_{17} \cdot U \cdot W^2 \quad .$$
$$+ b_{18} \cdot V^2 \cdot W + b_{19} \cdot U^2 \cdot W + b_{20} \cdot W^3$$

Likewise, the sample RPC models is expressed as

$$s = \frac{Num_S(U,V,W)}{Den_S(U,V,W)}$$

where again Num_S and Den_S are cubic functions of object space coordinates, *U*, *V*, and *W* are normalized object space coordinates (latitude, longitude, height), and *l* and *s* are normalized image space coordinates (line, sample).

RPC Accuracy Analysis

Accuracy of the RPC model was determined using the approach shown in Figure 7. For a number of imaging scenarios the RPC model was estimated from a 3-dimensional grid of points in the object space generated using the physical IKONOS camera model. In addition, a grid of independent check points was generated which was later used to compute accuracy of the RPC model.

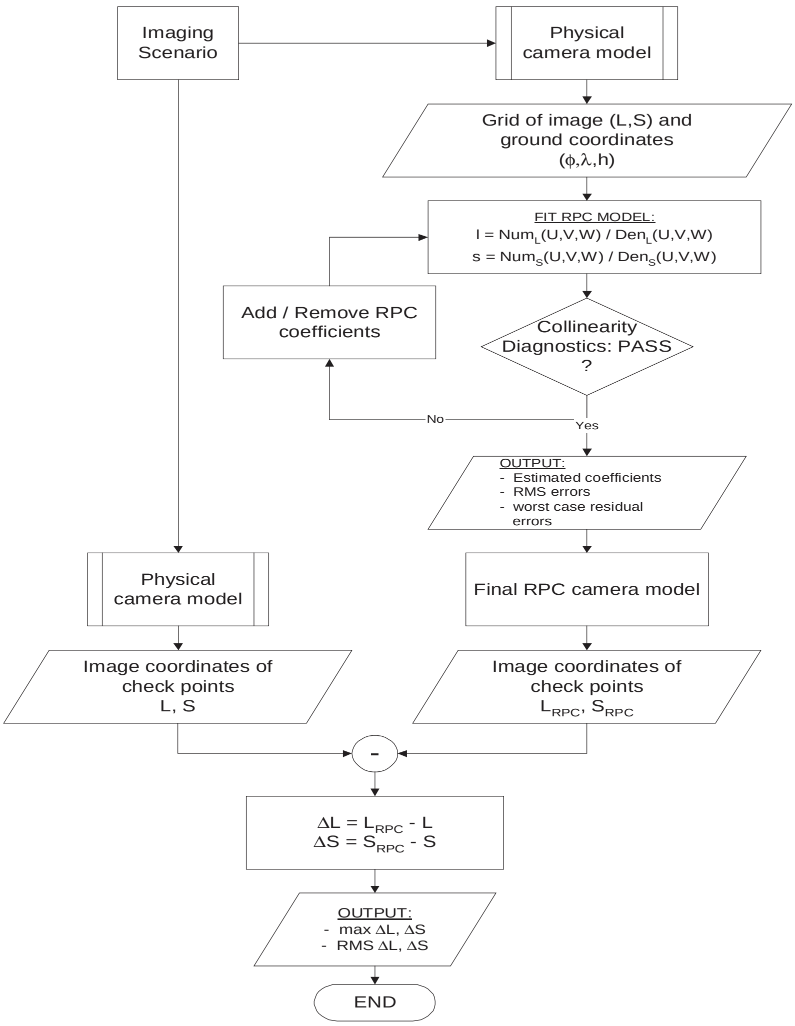


Fig. 7. RPC Accuracy Analysis

RPC Estimation

A least-squares approach was utilized to determine the RPC model coefficients from a 3-dimensional grid of points generated using the physical IKONOS camera model. The 3-D grid of object points was generated by intersecting rays emanating from a 2-D grid of image points – computed using the physical IKONOS camera model – with a number of constant elevation planes (see Figure 8).

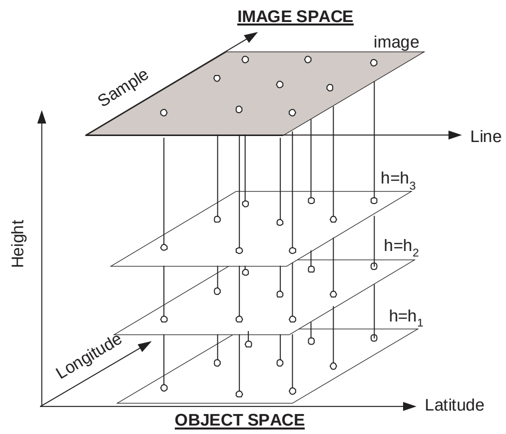


Figure 8. RPC Estimation

RPC Accuracy Results

RPC accuracy (see Table 5) was computed for the following imaging scenarios

- strip length of 100 km,
- roll and pitch angle of the camera ranged from 0^o to 30^o,
- scan azimuth ranged from 0^o through 360^o,
- latitude ranged from $0^o$to 60^o.

Table 5. RPC Accuracy

RPC model	Post-fit RMS error [pixels]	RMS error using independent check points [pixels]	Max error using independent check points [pixels]
line	0.01	0.01	0.04
sample	0.01	0.01	0.03

ON-ORBIT ACCURACY VERIFICATION

RPC Accuracy Verification

The accuracy of the RPC sensor model was verified empirically by comparing a number of IKONOS products generated at Space Imaging with both the physical IKONOS camera model and the RPC camera model, over the past year. As expected, no discernable differences between the products generated with both methods were found.

Geometric Accuracy Verification

The IKONOS geometric accuracy was verified by an On-Orbit Verification program. The geometric accuracy was determined empirically by comparing IKONOS images against the known ground control over the Space Imaging metric test ranges. For stereo images the GCP locations were measured in 3D on a softcopy photogrammetric workstation. This allowed to estimate both the horizontal and the vertical errors. For monoscopic images the horizontal errors were computed by back tracing the known GCPs to the image coordinate space, using the IKONOS camera model, and measuring the offsets between the predicted and the actual locations of the photo-identifiable GCPs on the image. Early accuracy results for georectified and orthorectified products are given in [Dial, 2000]. In this study two Level 2 and two Level 3 stereo pairs, taken over the San Diego metric test range, were compared against a set of well distributed check points. The San Diego test range used in this study consists of 140 GCP over a 22 by 22km area.

As seen in Figure 9 and 10, for uncontrolled stereo images, the horizontal accuracy was found to be 6 m and 4 m for both stereo pairs, while the vertical accuracy was determined to be at 1 m and 6 m level, respectively. It should be noted that in both cases the errors were distributed in a very narrow range, indicating high relative accuracy.

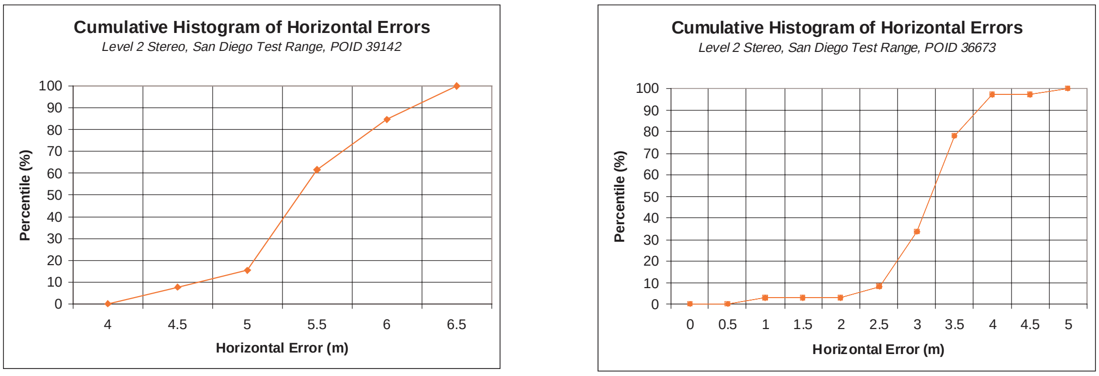


Figure 9. Level 2 Stereo Horizontal Errors

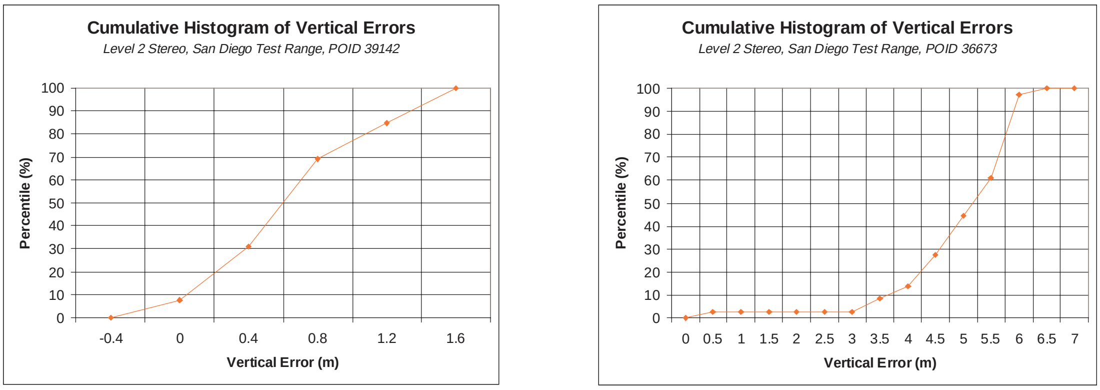
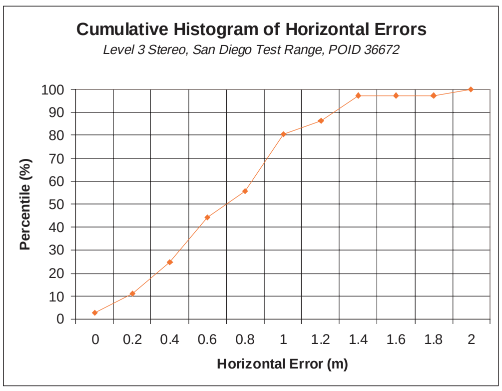


Figure 10. Level 2 Stereo Vertical Errors

The accuracy of GCP controlled stereo images is given in Figure 11 and Figure 12. In both cases the horizontal accuracy was of the order of 1 m while the vertical accuracy was of the order of 2 m.



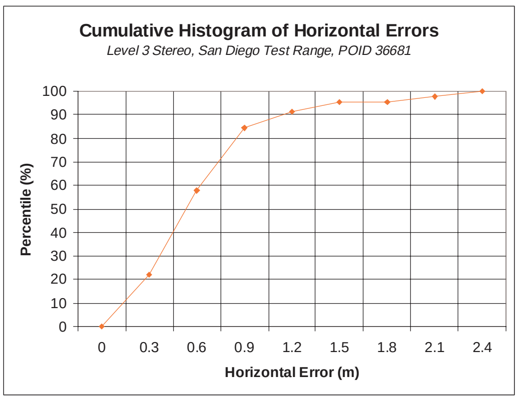
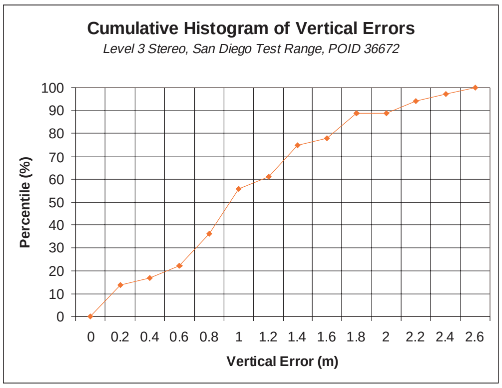


Figure 11. Level 3 Stereo Horizontal Errors



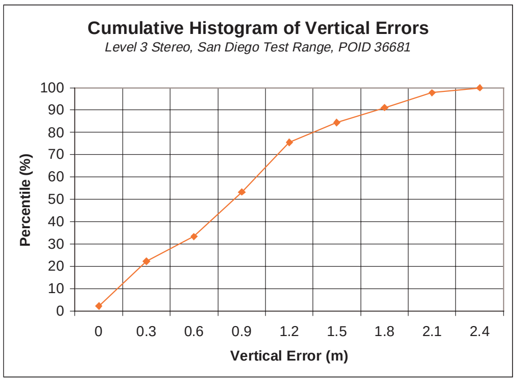


Figure 12. Level 3 Stereo Vertical Errors

CONCLUSIONS

IKONOS is an agile, high resolution, imaging satellite in sun-synchronous orbit. Exterior and interior orientation are determined a-priori by on-board sensors and on-orbit calibration. The 4-band multispectral sensor approximates Landsat bands 1-4 with 4m resolution. The panchromatic sensor provides 1m resolution. While image geometry can be approximated by the sensor azimuth and elevation angles, the physical camera model is precisely described by RPC coefficients. An extensive analysis of RPC accuracy shows worst-case differences below 0.05 pixels when compared to the camera model. The IKONOS RPC camera model provides a simple yet accurate way to communicate IKONOS image geometry to end users. The geometric characteristics and accuracy of Georectified, Orthorectified, and Stereo products have been described. Standard and Precision Stereo accuracy was tested with test range imagery. The high geometric and radiometric accuracy of IKONOS images make them ideally suited for automated classification and mapping applications.

REFERENCES

Dial, G. (2000). IKONOS satellite mapping accuracy. *ASPRS 2000 Proceedings*, Washington DC, 22-26 May 2000.

Grodecki, J. (2001). IKONOS stereo feature extraction - RPC approach. *ASPRS 2001 Proceedings*, St. Louis, MO, 23-27 April 2001.

Mikhail, E.M., Bethel, J.S., McGlone, J.C. (2001). *Introduction to Modern Photogrammetry*. J. Wiley, New York.

Space Imaging (2001). " IKONOS Relative Spectral Response ", Space Imaging Document http://www.spaceimaging.com/aboutus/satellites/IKONOS/spectral.htm