IKONOS ACCURACY WITHOUT GROUND CONTROL

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ABSTRACT:

The ground-to-image relationship of an IKONOS image is described by its nominal RPC camera geometry supplemented with bias and drift parameters. Experimental data shows that the RMS bias is 4-meters and the RMS drift is 50 PPM. Residual errors after bias and drift correction are 0.5 meters RMS. A mathematical model to estimate ground coordinates from block-adjusted imagery is developed. Experimental results for this point measurement process will be presented at the conference.

1. INTRODUCTION

The IKONOS camera model has been described by Rational Polynomial Coefficient (RPC) equations. The RPC model has been applied to feature extraction problems (Grodecki, 2001). IKONOS accuracy has been evaluated by the deviations from the RPC model (Dial, 2001; Grodecki and Dial 2001; Dial and Grodecki 2002a). The RPC camera model has been extended for bundle block adjustment (Dial and Grodecki 2002b; Grodecki and Dial 2002b) by adding bias and drift parameters. Here we evaluate the bias and drift parameters for an ensemble of imagery to establish RMS values for those parameters. The RMS parameter values can be used as a-priori to a block adjustment process. We extend the block adjustment process to provide optimal position and covariance estimates of points within the image. An example of point position estimation is shown with errors compared to covariances.

2. RPC CAMERA MODEL

The geometric relationship between 3-D ground coordinates and 2-D image coordinates is provided by the RPC camera model equations:

$$\begin{aligned} L &= R_L(f, l, h) \\ S &= R_S(f, l, h) \end{aligned} \quad (1)$$

where

$(f,\ l,\ h)$ = latitude, longitude, and height,
L = image line number,
S = image sample number, and
R_L, R_S = rational function for line and sample.

The detailed equations for rational functions R_L and R_S may be found in (Grodecki 2001) with formatting details in (Space Imaging, 2001). Here we simply use functional notation R_L and R_S. RPC equations from Space Imaging ground stations are fit to the physical camera model after block adjustment and so have the absolute accuracy resulting from that block adjustment process. Reference stereo images are 15-meter CE90 and Precision stereo images are 4m CE90 or better. The supplied RPC equations are useful for 3D feature extraction applications such as terrain extraction or building height determination (Grodecki, 2001).

If IKONOS imagery is to be block adjusted outside of the ground stations, then the RPC equations are augmented with bias, drift, and residual error terms:

$$\begin{aligned} L &= R_L(f,\ l, h) + a_o + a_L L + v_L \\ S &= R_S(f,\ l, h) + b_o + b_L L + v_S \end{aligned} \quad (2)$$

where

$(f,\ l,\ h)$ = latitude, longitude, and height,
L = image line number,
S = image sample number,
R_L, R_S = rational function for line and sample,
a_o, b_o = bias parameters for line and sample,
a_L, b_L = drift parameters for line and sample,
v_L, v_L = residual errors for line and sample.

In the above, R_L and R_S are the nominal ground to image relationship provided with the image. Bias parameters (a_o,b_o) adjust for any bias errors in satellite attitude or ephemeris. Satellite attitude and ephemeris errors are not independently observable, so their effects are lumped together into these image line and sample biases. Line number, L, is a surrogate for time so that drift parameters (a_L, b_L) adjust for any temporally linear error in satellite attitude. We will see that drift rates are ~50ppm, so whether we use the nominal or measured line number for L is not of quantitative significance. See (Dial and Grodecki 2002b; Grodecki and Dial 2002b) for a more complete description of RPC block adjustment of high-resolution satellite imagery. Use of equation (2) in a block adjustment process requires knowledge of the RMS uncertainty of the bias, drift, and image residual parameters. Those same bias, drift, and residual RMS values will be used to characterize IKONOS accuracy without ground control.

3. RPC CAMERA MODEL ERRORS

A collection of 18 image strips over Puerto Rico was used to test IKONOS accuracy without ground control. The images were 20 to 55km long. At least 4 GPS-surveyed ground control points (GCP) were available for each image. The images were processed individually without using the ground control. The images were georectified to constant elevation and nominal RPC camera model data was calculated (as in the Space Imaging "Ortho-Kit" commercial product). The known GCP (ground control point) coordinates were input to equation (1) to calculate the nominal line and sample image position of each GCP. The image was inspected around the nominal image position, the GCP was visually identified, and the actual line and sample position was measured. The image position errors were then calculated:

$$dX = S_M - R_S(j_G, l_G, h_G)$$
$$dY = L_M - R_L(j_G, l_G, h_G) \qquad (3)$$

where

S_M, L_M = measured GCP sample and line,
dX, dY = image position error East and North, and
(j_G, l_G, h_G) = GCP latitude, longitude, and height.

A scatter plot of image position errors for these 18 strips is shown below.

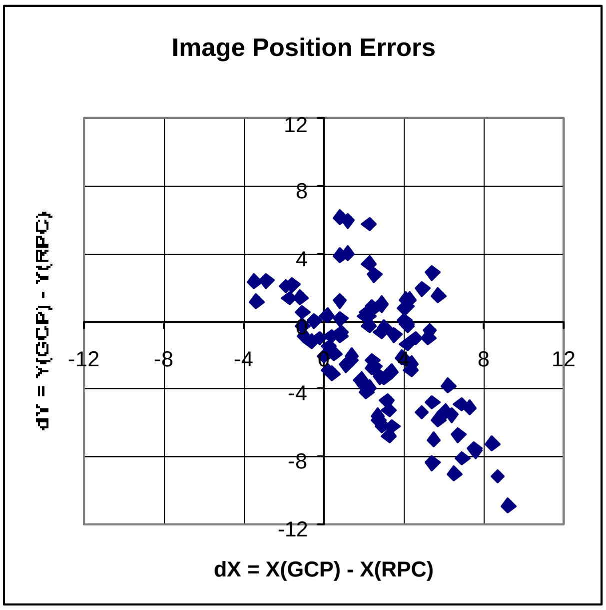

Fig. 1. Scatter plot of image position errors

The cause of the error bias and correlation evident in figure 1 is presently unknown but being investigated.

A plot of image position error versus line number for one sample image is shown below with dX in blue and dY in red.

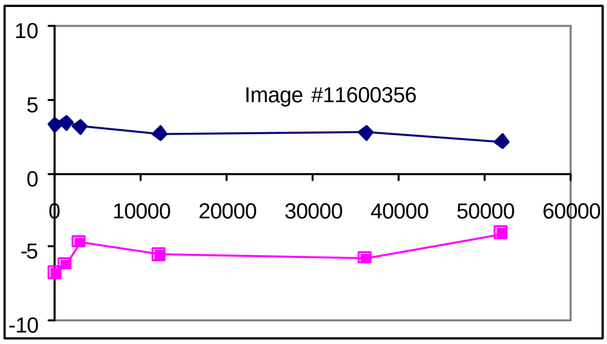

Fig. 2. Position error versus line number for a typical image

This particular image has bias of about 3 pixels in X, -5 pixels in red, and small drift rates. The biases and slopes in X and Y were determined for each of the 18 images by least-squares.

3.1 Image Bias Statistics

The X and Y biases determined by least-square fit to the 18 images are shown in the scatter plot below.

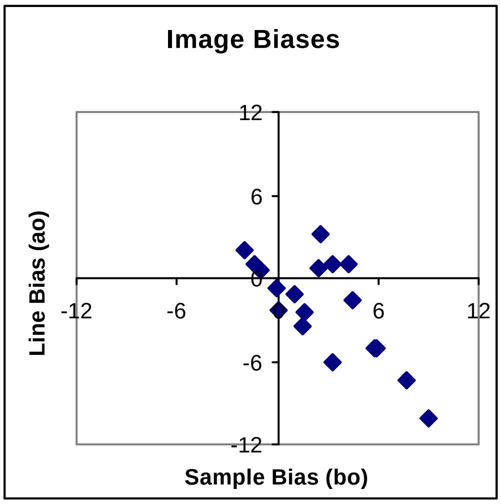

Fig. 3. Scatter plot of Image Biases

The bias is 4 meters RMS per axis. The non-zero average and correlation are again evident. The non-zero average is included in the reported 4m RMS value.

3.2 Image Drift Statistics

The units of drift are pixels per meter or, in the case of one-meter pixels, meters per meter. This however results in inconveniently small numbers. So we will report drift in parts-per-million or ppm. A scatter plot of the 18 image drifts is shown below.

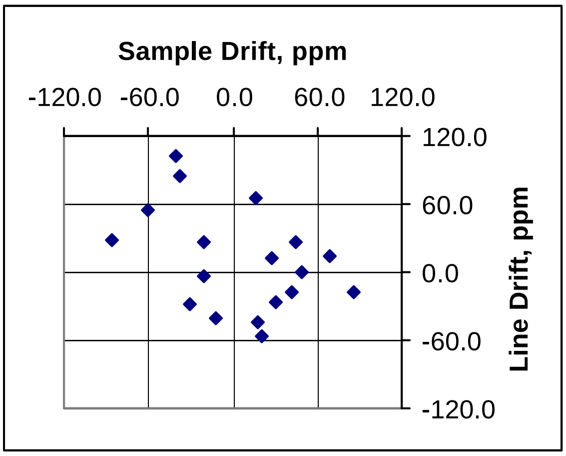

Fig. 4. Scatter plot of Line and Sample Drifts

The RMS drift for these 18 images is 46 ppm. This corresponds to a drift of 4.6 pixels (or meters) in a 100km long strip. For comparison, 1-degree of latitude is 111km. So the end-to-end relative error of a 1-degree long strip is less than 5 meters.

3.3 Residual Error Statistics

After correction for least square fit bias and drift, the residual errors for the 98 GCP on the 18 strips are shown in the scatter plot below.

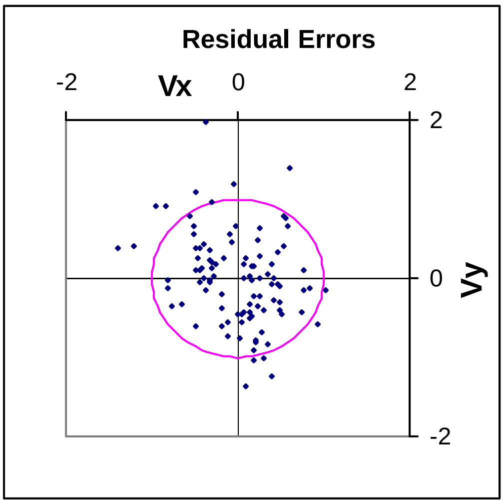

Fig. 5. Residual errors after bias and drift removal

The RMS residual error is 0.52 pixels. A circle with 1 pixel radius is drawn for reference.

4. IKONOS ACCURACY SUMMARIZED

The RPC adjustment model is given by equation (1).

$$L = R_L(f, l, h) + a_o + a_L L + v_L \quad (1)$$
$$S = R_S(f, l, h) + b_o + b_L L + v_S$$

The a-priori RMS values for the adjustable parameters are given in Table 1 below.

Symbol	Description	RMS
a_0	Line Offset	4.0 meters
b_0	Sample Offset	4.0 meters
a_L	Line Drift Rate	50 PPM
b_L	Sample Drift Rate	50 PPM
v_L	Line Residual	0.5 pixels
v_S	Sample Residual	0.5 pixels

Table 1. Summary of parameter a-priori

These a-priori values are appropriate for individual IKONOS image strips that have not been block adjusted in the ground station.

5. POINT POSITION MEASUREMENT

Accuracy has been described as the accuracy with which image coordinates can be predicted. Here we address the question of how accurately ground coordinates can be determined from image measurements. We begin by deriving a process to optimally estimate ground coordinates from multiple image measurements.
First the images are block adjusted and then measurements are processed to determine point positions. This two-step process is illustrated below.

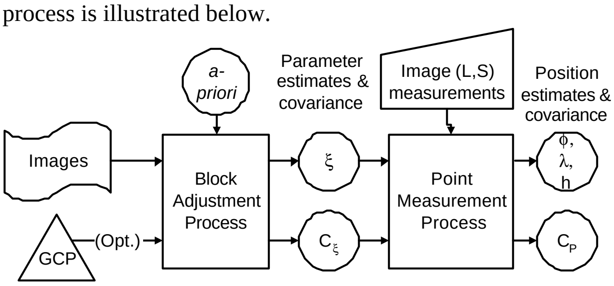

Fig. 6. Point Measurement after block adjustment

The block adjustment process is first. The tie points and optional ground control points are measured. The a-priori provides expected values and covariances of the bias and drift parameters for each image and eliminating any "datum defect" that might have otherwise resulted from the absence of ground control. The measurements, control, and a-priori are adjusted together by least squares in the block adjustment process.

The Point Measurement Process follows. The a-posteriori parameter estimates and covariances from the block adjust process become a-priori to the point measurement process. Ground positions are calculated from the image measurements and adjustments. Uncertainty in the image adjustment is propagated into the error covariance of the estimated position.

5.1 Scenario

A typical scenario would be measuring a ground coordinate from two or more images each described by RPC data. These images might be part of a stereo pair or triplet or they might be multiple monoscopic images from different orbital passes as for cross-track stereo. The scenario is illustrated below for two source images.

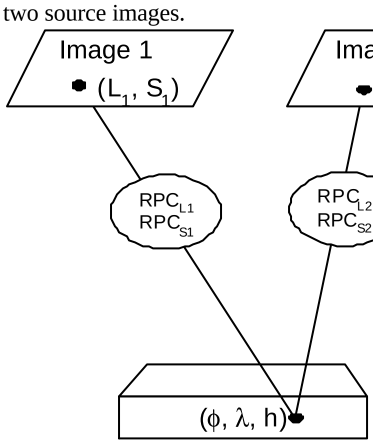

Fig 7. Measuring an object position from two images

5.2 A-priori Information

The parameter estimates, ξ, and covariance matrix, C_ξ, from the block adjustment process become a-priori to the point measurement process. For two images

$$\begin{aligned} x &= (a_{01}, a_{L1}, b_{01}, b_{L1}, a_{02}, a_{L2}, b_{02}, b_{L2}) \\ C_x &= Cov\{x\} \\ &= Cov\{a_{01}, a_{L1}, b_{01}, b_{L1}, a_{02}, a_{L2}, b_{02}, b_{L2}\} \end{aligned} \tag{4}$$

where

x = adjusted parameter vector,

C_x = covariance of parameter vector x ,

(a_{oi}, b_{oi}) = adjusted offsets for image *i*, and

(a_{Li}, b_{Li}) = adjusted drift terms for image *i*.

Block adjustment provides improved parameter estimates and covariance for use during the point measurement process.

5.3 Observation Equations

A point at unknown coordinate $(j,\ l,\ h)$ is measured in each image providing image coordinates $(L_i,\ S_i)$. Those measurements are input to the observation equation (5).

$$\begin{aligned} &\frac{\partial R_{Li}}{\partial j}\Delta j + \frac{\partial R_{Li}}{\partial l}\Delta l + \frac{\partial R_{Li}}{\partial h}\Delta h + a_{oi} + a_{L1}L_i + v_{Li} \\ &\quad = L_i - R_{Li}(f_0, l_0, h_0) \\ &\frac{\partial R_{Si}}{\partial j}\Delta j + \frac{\partial R_{Si}}{\partial l}\Delta l + \frac{\partial R_{Si}}{\partial h}\Delta h + b_{oi} + b_{Li}L_i + v_{Si} \\ &\quad = S_i - R_{Si}(f_0, l_0, h_0) \end{aligned} \tag{5}$$

where

(L_i, S_i) = target coordinate on image *i*,

(R_{Li}, R_{Si}) = image *i* line, sample RPC functions,

$(f_o,\ l_o,\ h_o)$ = initial latitude, longitude, and height,

$Df,\ Dl,\ Dh$ = latitude, longitude, height increment,

(v_{Li}, v_{Si}) = line and sample residual on image *i*.

5.4 Least-Square Solution to Point Measurement Problem

Initial estimates of the parameters are formed into a vector

$$x_0 = (a_{01}, a_{L1}, b_{01}, b_{L1}, a_{02}, a_{02}, b_{02}, b_{L2}, f_0,\ l_0, h_0)^T .$$

The a-priori and observation equations are combined into the matrix least-square problem to estimate correction Dx to parameter vector x as shown in equation (6) set at the end of the document where

$$\Delta x = (\Delta a_{01}, \Delta a_{L1}, \Delta b_{01}, \Delta b_{L1}, \Delta a_{02}, \Delta a_{02}, \Delta b_{02}, \Delta b_{L2}, \Delta f, \Delta l, \Delta h)^T .$$

This is an over-determined equation of the form $A\ Dx = y + v$. The residual error covariance matrix is

$$C_v = Cov\{a_{01}, a_{L1}, b_{01}, b_{L1}, a_{02}, a_{02}, b_{02}, b_{L2}, v_{L1}, v_{S1}, v_{L2}, v_{S2}\}$$

$$= \begin{bmatrix} C_x & 0 & 0 & 0 & 0 \\ 0 & s_p^2 & 0 & 0 & 0 \\ 0 & 0 & s_p^2 & 0 & 0 \\ 0 & 0 & 0 & s_p^2 & 0 \\ 0 & 0 & 0 & 0 & s_p^2 \end{bmatrix} \tag{7}$$

with s_p = RMS image residual ~ 0.5 pixels. These equations have least-square solution

$$\Delta x = (A^T C_v^{-1} A) A^T C_v^{-1}\ y \qquad (8).$$

The parameter vector x is updated by $x = x_o + Dx$ and the solution is iterated until convergence. Then the estimation error covariance can be calculated by

$$\begin{aligned} C_x &= Cov\{\Delta a_{01}, \Delta a_{L1}, \Delta b_{01}, \Delta b_{L1}, \Delta a_{02}, \Delta a_{02}, \Delta b_{02}, \Delta b_{L2}, \Delta f, \Delta l, \Delta h\} \\ &= (A^T C_v^{-1} A)^{-1}. \end{aligned} \tag{9}$$

The desired covariance of the latitude, longitude, and height measurement is just the bottom-right 3x3 portion of matrix C_x. The point measurement process thus determines both an optimal estimate of the ground coordinate and the error covariance of that estimate.

6. POINT POSITIONING EXAMPLE

The authors would like to have had a statistically significant number of experimental examples of the point positioning technique to include in this paper, but the copy deadline is upon us and the experimental results are incomplete, so this part of the paper will have to wait for the conference presentation. We hope to see you there.

7. CONCLUSIONS

The ground-to-image relationship of IKONOS images is described by the nominal RPC camera geometry supplemented with image-space bias and drift parameters. Experimental data shows that the RMS bias is 4-meters and the RMS drift is 50 PPM. Residual errors are 0.5 meters RMS. The mathematics for least-square point measurements has been developed. Experimental results for the point measurement process will be presented at the conference.

8. REFERENCES

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$$
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
1 & L_1 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{\partial R_{L1}}{\partial f} & \frac{\partial R_{L1}}{\partial l} & \frac{\partial R_{L1}}{\partial h} \\
0 & 0 & 1 & L_1 & 0 & 0 & 0 & 0 & \frac{\partial R_{S1}}{\partial f} & \frac{\partial R_{S1}}{\partial l} & \frac{\partial R_{S1}}{\partial h} \\
0 & 0 & 0 & 0 & 1 & L_2 & 0 & 0 & \frac{\partial R_{L2}}{\partial f} & \frac{\partial R_{L2}}{\partial l} & \frac{\partial R_{L2}}{\partial h} \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & L_2 & \frac{\partial R_{S2}}{\partial f} & \frac{\partial R_{S2}}{\partial l} & \frac{\partial R_{S2}}{\partial h}
\end{bmatrix}
\begin{bmatrix}
\Delta a_{01} \\ \Delta a_{L1} \\ \Delta b_{01} \\ \Delta b_{L1} \\ \Delta a_{02} \\ \Delta a_{L2} \\ \Delta b_{02} \\ \Delta b_{L2} \\ \Delta f \\ \Delta l \\ \Delta h
\end{bmatrix}
=
\begin{bmatrix}
-a_{01} \\ -L_1 a_{L1} \\ -b_{01} \\ -L_1 b_{L1} \\ -a_{02} \\ -L_2 a_{L2} \\ -b_{02} \\ -L_2 b_{L2} \\
L_1 - R_{L1}(f_o, l_o, h_o) \\ S_1 - R_{S1}(f_o, l_o, h_o) \\ L_2 - R_{L2}(f_o, l_o, h_o) \\ S_2 - R_{S2}(f_o, l_o, h_o)
\end{bmatrix}
\qquad (6)
$$