WorldView-3 Geolocation Accuracy and Band Co-Registration Analysis

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2016 Joint Agency Commercial Imagery Evaluation (JACIE) Workshop
Outline

Background

Methodology

Results
DigitalGlobe WorldView-3 Satellite

Metric Design and Internal Geometric Calibration

Direct Geolocation

- GPS receiver on-board used to determine orbital position
- Inertial Reference Units and Star Trackers used to determine pointing direction
- Sensor and its relationship to GPS and star trackers are highly calibrated

0.31 m Panchromatic (Pan)
1.24 m 8-Band Multispectral (MSI)
3.7 m Shortwave Infrared (SWIR)
30 m Clouds, Aerosols, Vapor, Ice, Snow (CAVIS)
Physical Sensor Model (PM)

Relates ground positions to image pixels by modeling geometry of imaging
- Includes input of calibrated sensor parameters such as focal length and detector locations
- Includes input of satellite position and pointing at any given time

These inputs conveyed via image metadata

Sensor models can also predict ground point errors using input uncertainties
- Known as Error Propagation

Used Basic 1B Community Sensor Model (CSM)
Rational Polynomial Coefficients (RPC) Model

Relates image pixels to ground positions, but using ratio of 3\textsuperscript{rd} order polynomial equations

\[
\text{image row} = f_1(\text{lat, long, height}) \\
\text{image column} = f_2(\text{lat, long, height})
\]

Coefficients fit to physical sensor model by DigitalGlobe

“Replaces” physical sensor model
Simpler model for software lacking complicated physical sensor model

Used RPC CSM
Geometry of DigitalGlobe Product Processing

Staggered Pushbroom Array (what is actually collected)

- Multiple, overlapping “sub-images”
- Not available from DG

Basic 1B Product
- Synthetic Pushbroom Array
- Image not on map grid (i.e., “raw’)
  - Both pushbroom physical model and RPC replacement model

Ortho-Ready Standard 2A Product
- Rectified to fixed height above ellipsoid (average elevation)
- On map grid, but significant terrain relief distortion if using map grid
  - However, RPC replacement model data available for geolocation comparable to Basic 1B

Standard 2A or Orthorectified 3X
- Orthorectified to terrain model
- On map grid, although only terrain as modeled is corrected
## Test Matrix

<table>
<thead>
<tr>
<th>Test</th>
<th>WorldView-3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pan</td>
</tr>
<tr>
<td>Absolute Geolocation Accuracy (&quot;How close to true geolocation?&quot;)</td>
<td>B1B</td>
</tr>
<tr>
<td>Error Propagation (&quot;How realistic is accuracy prediction?&quot;)</td>
<td>B1B</td>
</tr>
<tr>
<td>Band-to-Band Co-registration (&quot;How well do bands align within image?&quot;)</td>
<td>B1B, OR2A</td>
</tr>
<tr>
<td>Sensor Co-registration (&quot;How well do co-boresighted images align?&quot;)</td>
<td>B1B</td>
</tr>
<tr>
<td>RPC Fit to Physical Model (&quot;RPC- vs. PM-derived coordinates&quot;)</td>
<td>B1B</td>
</tr>
</tbody>
</table>
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Absolute Geolocation Accuracy, Error Propagation, Sensor Co-registration, and RPC Fit Analysis – Mono Intersection

2-D coordinates (Latitude, Longitude) from mono intersection to true height
...and error estimate

True 3-D coordinates of image-identifiable, ground-surveyed point, including height

2-D Error
(\(\Delta\) Easting, \(\Delta\) Northing)
Absolute Geolocation Accuracy – Ground Truth

Terminal Aeronautical Global Navigation Satellite System (GNSS) Geodetic Survey (TAGGS) Program

Provides accurately-surveyed coordinates for aerodromes

- Runways
- Navigation aids
- Vertical obstructions
- Ground Control Points (GCPs)

Supports safety of air navigation

Typically 0.25m (1σ) accuracy in each coordinate direction
Absolute Geolocation Accuracy – Consolidated Errors

Test sites have varying number of check points

To weight each image equally, consolidate check point errors into single data point for each image

Use error centroid
  ► Compute mean “Δ Easting” and “Δ Northing” values
    • Convert into horizontal “Δ Radial” value

“Δ Radial” used to estimate Horizontal Error 90% (HE90)
Absolute Geolocation Accuracy – Ordered Statistics 90% Error Estimation

Mono HE90 value estimated by sorting “Δ Radial” error from each image by magnitude and cutting off at 90%

Cutoff formula = 0.9n + 0.5 in which n is number of images

HE90 values linearly interpolated to cutoff position

Done separately for Physical Model and RPC support data

Non-parametric confidence estimated as well
Measuring Co-Registration Accuracy

Many methods have been devised for registering images and estimating registration accuracy [1]

- Spatial Correlation Methods—spatial similarity comparing features in image pairs
- Fourier Methods—correlation of image data in the frequency domain—phase correlation
- Mutual Information Methods—comparing the statistical dependence of two image data sets
- Variations on these and other methods

Many of the same techniques can be adapted to measure residual registration errors

Of particular utility is the Phase Correlation Method [2][3], a Fourier technique

- Combined with other techniques these can obtain sub-pixel registration accuracy estimates [4] [6]
- Method robust to noise and speckle [5]
Band Co-Registration Measurement Algorithm

Uses well-known phase correlation method

► Shift of one band with respect to another band in the spatial domain corresponds to a phase shift in the frequency domain—a consequence of the Fourier shift theorem

1) For any two co-registered bands with same dimensions, determine the number \(N\) of \(n \times n\) pixel samples in either band
2) Obtain corresponding samples from each band
3) Generate the correlation surface for each sample pair
   a) The amplitude of the coherent peak is a measure of the degree of congruence between the two samples
   b) The coherent peak centers at the point of co-registration and estimates the co-registration error to pixel accuracy
   c) The center of mass of a 5 x 5 window centered on the coherent peak estimates the sub-pixel errors in the x- and y-directions
4) Determine the errors for all \(N\) samples
5) Calculate the mean magnitude, \(\Delta r\), and standard deviation of the errors over all \(N \times n \times n\) samples
Example Co-Registration Accuracy Measurement

GeoEye-1 MSI Image: Green Band Relative to Blue Band

<table>
<thead>
<tr>
<th>Registration Errors (pixels)</th>
<th>266 Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>152</td>
<td>0.069</td>
</tr>
<tr>
<td>162</td>
<td>0.133</td>
</tr>
<tr>
<td>172</td>
<td>0.045</td>
</tr>
<tr>
<td>182</td>
<td>0.143</td>
</tr>
<tr>
<td>192</td>
<td>0.096</td>
</tr>
<tr>
<td>202</td>
<td>0.078</td>
</tr>
<tr>
<td>212</td>
<td>0.175</td>
</tr>
<tr>
<td>222</td>
<td>0.161</td>
</tr>
<tr>
<td>232</td>
<td>0.133</td>
</tr>
<tr>
<td>242</td>
<td>0.184</td>
</tr>
<tr>
<td>252</td>
<td>0.133</td>
</tr>
<tr>
<td>262</td>
<td>0.083</td>
</tr>
<tr>
<td>272</td>
<td>0.138</td>
</tr>
<tr>
<td>282</td>
<td>0.114</td>
</tr>
</tbody>
</table>

*Correlation indicates the degree of congruence between the reference and the match sample—a function of the registration error and the noise

Uses Phase Correlation Method

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Outline

Background

Methodology

Results
WV03 Absolute Geolocation Accuracy Results

Using no Ground Control Points

<table>
<thead>
<tr>
<th>Sample size of 27 WorldView-3 Basic 1B Mono Images (Physical Model)</th>
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<tbody>
<tr>
<td>Sample Mono HE90 (m)</td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>Panchromatic</td>
</tr>
<tr>
<td>8-Band MSI</td>
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<td>8-Band SWIR</td>
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</table>
WV03 Basic 1B Pan Mono Geolocation Accuracy

Basic 1B CSM HE90 = 2.8m

Δ North (m)

Δ East (m)

WV03 RPC Error Centroids
WV03 RPC Mean
WV03 Basic 1B CSM Error Centroids
WV03 Basic 1B CSM Mean

Basic 1B CSM Mean: (0.3m, -0.4m)
RPC Mean: (0.4m, -0.4m)
Error Propagation Analysis

Realism of predicted accuracy of ground coordinates visualized through a plot

- Measured errors on y-axis
- Predicted 90% errors on x-axis
- If prediction is realistic, measured errors should be less than predicted errors 90% of the time
  - Demarked by slope = 1 line
WV03 Error Propagation Summary

<table>
<thead>
<tr>
<th>Error Propagation (% Below Slope = 1 Line)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All 217 Points</td>
</tr>
<tr>
<td>Panchromatic</td>
</tr>
<tr>
<td>8-Band MSI</td>
</tr>
<tr>
<td>8-Band SWIR</td>
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<th>Error Propagation (% Below Slope = 1 Line)</th>
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<td>Based on Ave for 27 Images</td>
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<tr>
<td>Panchromatic</td>
</tr>
<tr>
<td>8-Band MSI</td>
</tr>
<tr>
<td>8-Band SWIR</td>
</tr>
</tbody>
</table>

- Ideally values should be 90%
WV03 Sensor Co-Registration

Same 217 points measured in Pan, MSI, and SWIR images
Images related using Basic 1B photogrammetric sensor models

<table>
<thead>
<tr>
<th></th>
<th>Physical Model RMSE</th>
<th>RPC RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSI - Pan</td>
<td>1.6 m (1.3 pixels)</td>
<td>1.2 m (0.9 pixels)</td>
</tr>
<tr>
<td>SWIR - Pan</td>
<td>4.3 m (1.2 pixels)</td>
<td>3.3 m (0.9 pixels)</td>
</tr>
<tr>
<td>SWIR - MSI</td>
<td>3.3 m (0.9 pixels)</td>
<td>2.7 m (0.7 pixels)</td>
</tr>
</tbody>
</table>
RPC Fit Analysis

Goal is to confirm that RPC data provides comparable geolocation as Physical Sensor Model data

► RPC parameters were fit to Physical Model by DigitalGlobe Methodology

► For each image, create a pixel grid across image with uniform spacing in row and column
► Separately for RPC and the Physical Model, determine horizontal ground coordinates for each pixel grid location at elevation plane near ground
► Determine the difference in horizontal ground coordinates at each grid location
► Estimate overall statistics, including maximum differences
► Generate quiver plot for visualization
Example Plot: Keetmanshoop, Namibia (WV03 Pan)

NA-Keetmanshoop-Namibia
15JUL13090619-P1BS-500407397190-01-P001

Height Plane: 1035 m

Easting/Northing Differences
mean: (0.0m, 0.2m)
max: (0.1m, 0.4m)
min: (-0.1m, 0.0m)

Max Quiver Magnitude: 0.4m

North Arrow Direction: 180 deg

Quiver Scale: 2000 pixels/m

(Scaled quivers may cause negative rows/cols in plot.)
Example Plot: Keetmanshoop, Namibia (WV03 MSI)

Difference between Physical Model and RPC Geolocation

NA-Keetmanshoop-Namibia
15JUL13090619-M1BS-500407397190-01-P001

Height Plane: 1035 m

Easting/Northing Differences
mean: (0.0m, 0.7m)
max: (0.1m, 1.3m)
min: (-0.1m, 0.1m)

Max Quiver Magnitude: 1.3m
North Arrow Direction: 180 deg
Quiver Scale: 250 pixels/m

(Scaled quivers may cause negative rows/cols in plot.)
Example Plot: Keetmanshoop, Namibia (WV03 SWIR)

Difference between Physical Model and RPC Geolocation

NA-Keetmanshoop-Namibia
15JUL13090618-A1BS-500407397210-01-P001

Height Plane: 1036 m

Eastings/Northings Differences
- mean: (-0.0m, 1.9m)
- max: (0.5m, 3.8m)
- min: (-0.5m, -0.0m)

Max Quiver Magnitude: 3.8m

North Arrow Direction: 180 deg

Quiver Scale: 75 pixels/m

(Scaled quivers may cause negative rows/cols in plot.)
WV03 Maximum Differences between RPC and Physical Model Geolocation

Normalized Maximum Magnitude (pixels)

Collection Date


NGA NATIONAL GEOSPATIAL-INTELLIGENCE AGENCY
Approved for Public Release Case 16-232
WorldView-3 Band Co-Registration Results

Visually reviewed all images
  ► All images cloud free

For each image, measured relative registration errors among all bands
  ► Band was selected as the reference band (1, 6, or 12)
  ► Measured registration accuracy in 128 x 128 pixel samples throughout image
  ► For each sample, registration accuracy was estimated in both the x- and y-directions
  ► Calculated the magnitude of the registration error of each sample
  ► The reported image registration error is the average of all samples
WorldView-3 SWIR Basic 1B/OR2A Band Co-Registration Results

Registration accuracy is adequate, goal < 0.25 pixels
Registration errors of all bands are less than 0.35 pixels relative to band 1
No difference between the Cubic Convolution and the Bilinear resampling at 95% confidence level
WorldView-3 CAVIS Basic 1B Band Co-Registration Results

Registration accuracy excellent
No difference between C1BA and C1BB at the 95% confidence level
WorldView-3 CAVIS OR2A Band Co-Registration Results

**Registration accuracy excellent**

### Mean Registration Error for OR2A versus Band

<table>
<thead>
<tr>
<th>Band Pairs</th>
<th>Registration Error (pixels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12:1</td>
<td>0.20</td>
</tr>
<tr>
<td>12:2</td>
<td>0.10</td>
</tr>
<tr>
<td>12:3</td>
<td>0.10</td>
</tr>
<tr>
<td>12:4</td>
<td>0.10</td>
</tr>
<tr>
<td>12:5</td>
<td>0.10</td>
</tr>
<tr>
<td>12:6</td>
<td>0.10</td>
</tr>
<tr>
<td>12:7</td>
<td>0.10</td>
</tr>
<tr>
<td>12:8</td>
<td>0.10</td>
</tr>
<tr>
<td>12:9</td>
<td>0.10</td>
</tr>
<tr>
<td>12:10</td>
<td>0.50</td>
</tr>
<tr>
<td>12:11</td>
<td>0.40</td>
</tr>
<tr>
<td>12:12</td>
<td>0.40</td>
</tr>
</tbody>
</table>

### Table: OR2A Registration Results

<table>
<thead>
<tr>
<th>#</th>
<th>IID</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15AUG09175648-C2AS-500461524010_01_P001</td>
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<tr>
<td>2</td>
<td>15MAR20084954-C2AS-500461524050_01_P001</td>
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</tbody>
</table>
WorldView-3 CAVIS Std 2A Band Co-Registration Results

Registration accuracy excellent

<table>
<thead>
<tr>
<th>#</th>
<th>IID</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15AUG05175848-C2AS-500453702010_01_P001</td>
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<tr>
<td>2</td>
<td>15MAR20849354-C2AS-500453702030_01_P001</td>
</tr>
<tr>
<td>3</td>
<td>15MAR04025395-C2AS-500453702060_01_P001</td>
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<td>4</td>
<td>15FEB28375417-C2AS-500453702070_01_P001</td>
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<td>10</td>
<td>15JAN20155718-C2AS-500453702140_01_P001</td>
</tr>
</tbody>
</table>

![Mean Registration Error for STD2A versus Band](chart)

Registration accuracy excellent
Summary

217 measured points on 27 Basic 1B images

► Absolute geolocation accuracy (no ground control points)
  • Panchromatic: 2.8-2.9 meters HE90
  • 8-Band MSI: 3.2-3.5 meters HE90
  • 8-Band SWIR: 4.6-5.9 meters HE90

► Error propagation and sensor co-registration results are reasonable

RPC fits Physical Model within 1 to 1.5 pixels

Band-to-Band co-registration

► SWIR bands within 0.35 pixels
► CAVIS bands within 0.25 pixels
Backups
Purposely introduced errors into a copy of the same image
Measured the registration errors between the original and copy

Mean Difference Between the Introduced and Measured Error
$= 0.022 \pm 0.0051; \text{ 90\% Conf.}$
References


