WorldView-3 Absolute Geolocation Accuracy Evaluation

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Outline

• Background

• Evaluation

• Results
WorldView-3

- Owned by DigitalGlobe (DG)
- Launched: 13 August 2014

- Direct geo-location
  - 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
Mono and Stereo Collection

- Agile scanning
  - Forward
  - Reverse
- Along-track stereo
- Off-nadir angles typically < 30°
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
Rational Polynomial Coefficients (RPC) Model

- Relates image pixels to ground positions, but using ratio of 3rd order polynomial equations
  \[ \text{image line} = f_1(\text{lat, long, height}) \]
  \[ \text{image sample} = f_2(\text{lat, long, height}) \]
- Coefficients fit to physical sensor model by DigitalGlobe
- “Replaces” physical sensor model
- Simpler model for software lacking complicated physical sensor model

Image Pixel  \(\rightarrow\) Image  \(\downarrow\) Rational Polynomial Equations with Coefficients  \(\rightarrow\) Ground Point

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Geometry of 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’)
• Sensor model data available for geolocation:
  1) Pushbroom physical model
  2) RPC replacement model

Ortho-Ready Standard 2A Product
• Plane rectified to fixed height (average elevation)
• On map grid, but terrain relief distortion not removed if geolocating using corner coordinates
• But, RPC replacement model data available for geolocation comparable to Basic 1B

Orthorectified Image
• To terrain (or surface) model
• On map grid, although objects not in model are not fully corrected

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Geolocation Accuracy Metrics

- **Predicted Accuracy**
  - **Horizontal**: Circular Error 90% (CE90)
  - **Vertical**: Linear Error 90% (LE90)
  - Applications:
    - Accuracy specifications
    - Error Propagation: Predicted accuracy of point ground coordinates from uncertainty of inputs and collection geometry

- **Estimated Accuracy from Sample Statistics**
  - TAGGS ground-surveyed points used as check points
  - Horizontal Error 90% (HE90) → used to verify WV03 CE90
  - Vertical Error 90% (VE90) → used to verify WV03 LE90

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Test Data

• 1\textsuperscript{st} Test Dataset
  – 51 Basic 1B Stereo Pairs (panchromatic)
  – 3 OR2A “Stereo Pairs” made from same input images as 3 of Basic 1B Stereo Pairs (panchromatic)

• 2\textsuperscript{nd} Test Dataset
  – 33 Basic 1B Stereo Pairs (panchromatic)

• Each stereo mate tested as a “mono” image
  – Grouped into “more nadir” and “more off-nadir” sets

• 8 Cases Total
  – Stereo, more nadir mono, and more off-nadir mono sets tested using both PM and RPC
    • Mono sets tested for horizontal accuracy
    • Stereo tested for horizontal and vertical accuracy

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Evaluations Performed

• **Geolocation**
  – **Absolute Geolocation Accuracy**
    “What is the accuracy performance of the WV03 satellite?”
  – **Error Propagation**
    “How realistic are accuracy predictions for ground points?”

• **Geolocation Consistency Check**
  – **Basic 1B vs. Ortho-Ready 2A (OR2A)**
    “Do OR2A products have comparable geolocation as Basic 1B products?” (Done for 3 stereo pairs)
  – **RPC Fit**
    “Does the RPC model provide a comparable ground point geolocation as the physical sensor model?”

• Assessed 2 ways
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

http://earth-info.nga.mil/GandG/geosurveys/TAGGS.html
Geolocation Analysis Testing Process

Ground Surveys:
Terminal Aeronautical GNSS Geodetic Surveys (TAGGS)

Test Stereo Pairs

Measure Points

Ground Truth
(check points)

Table and Charts

Automation

SOCET GXP v4.1

Generic Softcopy Exploitation Tool (GSET) and Community Sensor Models (CSMs)

Error Statistics

"Whole Image"
RPC Fit Check

Critical elements underlined

• Measure multiple ground points on many stereo pairs (prefer 25+)
• Geolocation errors from multiple points are consolidated into a single data point for each image or stereo pair

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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 (∆ Easting, ∆ Northing)
Stereo Intersection

Fixed 1st Mate

Fixed 2nd Mate

3-D coordinates (Latitude, Longitude, Height) from stereo pair intersection

...and error estimates

Measured Pixels

Image-to-ground

Image-to-ground

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

3-D Error
(Δ Easting, Δ Northing, Δ Height)
Consolidated Errors

• Test sites have varying number of check points
• To weight each image or stereo pairs equally, consolidate errors into single data point for each image and stereo pair
• Use error centroid
  – Compute mean “Δ Easting” and “Δ Northing” values
    • Convert into horizontal “Δ Radial” value
  – Compute mean “Δ Height” value (stereo pair only)
    • Convert into “absolute-value Δ Height” value
• “Δ Radial” and “absolute-value Δ Height” values used to estimate HE90 and VE90
Non-Parametric 90% Error Estimation

- Mono and Stereo HE90 values estimated by sorting “Δ Radial” error from each image/stereo pairs by magnitude and cutting off at 90%
- Stereo VE90 values estimated by sorting “absolute-value Δ Height” error from each stereo pair by magnitude and cutting off at 90%
- Cutoff formula = 0.9n + 0.5 in which n is number of image/stereo pairs
- HE90/VE90 values linearly interpolated to cutoff position
- Done separately for Physical Model and RPC support data
- Non-parametric confidence estimated as well
Fictitious Example
(90th Percentile Estimator)

Given an ordered sample set as follows (n=25):

\[ X_{(1)} = 14.1, X_{(2)} = 14.5, X_{(3)} = 14.6, X_{(4)} = 14.7, X_{(5)} = 14.8, X_{(6)} = 15.3, \]
\[ X_{(7)} = 15.4, X_{(8)} = 15.6, X_{(9)} = 15.7, X_{(10)} = 16.0, X_{(11)} = 16.1, X_{(12)} = 16.1, \]
\[ X_{(13)} = 16.2, X_{(14)} = 16.5, X_{(15)} = 16.7, X_{(16)} = 16.8, X_{(17)} = 17.1, X_{(18)} = 17.1, \]
\[ X_{(19)} = 17.3, X_{(20)} = 17.7, X_{(21)} = 17.8, X_{(22)} = 17.9, X_{(23)} = 18.3, X_{(24)} = 18.6, \]
\[ X_{(25)} = 20.1 \]

Estimated 90th percentile is \( X_{(23)} \) data point (18.3)

This is a simplified example in which the 90th percentile falls exactly at an ordered data point.

If n = 33 instead of n = 25, the 90% position would be \( 0.9 \times 33 + 0.5 = 30.2 \) → linearly interpolate between \( X_{(30)} \) and \( X_{(31)} \) values.
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WV03 Absolute Geolocation Accuracy Results

- Similar results between PM and RPC models
  - One way to assess RPC fit

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WV03 Basic 1B Mono Geolocation Accuracy (More Nadir Mates)

Basic 1B CSM HE90 = 3.8m

RPC HE90 = 3.9m

Basic 1B CSM Mean: (-0.7m, -0.7m)
RPC Mean: (-0.6m, -0.7m)
WV03 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

• For brevity, showing only 3 Physical Model cases
  – More nadir mono horizontal
  – Stereo horizontal
  – Stereo vertical
WV03 Basic 1B Physical Model Horizontal Error Propagation (More Nadir Mates)

- WV03 Basic 1B CSM (More Nadir)
- Slope = 1 Line

Below the Line: 87.9%
WV03 Error Propagation Summary

<table>
<thead>
<tr>
<th>Error Propagation (% Below Slope = 1 Line)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All 507 Points</td>
</tr>
<tr>
<td>Physical Model</td>
</tr>
<tr>
<td>RPC</td>
</tr>
<tr>
<td>More Nadir Mono Horizontal</td>
</tr>
<tr>
<td>More Off-Nadir Mono Horizontal</td>
</tr>
<tr>
<td>Stereo Horizontal</td>
</tr>
<tr>
<td>Stereo Vertical</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Error Propagation (% Below Slope = 1 Line)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Based on Ave for 33 Images</td>
</tr>
<tr>
<td>Physical Model</td>
</tr>
<tr>
<td>RPC</td>
</tr>
<tr>
<td>More Nadir Mono Horizontal</td>
</tr>
<tr>
<td>More Off-Nadir Mono Horizontal</td>
</tr>
<tr>
<td>Stereo Horizontal</td>
</tr>
<tr>
<td>Stereo Vertical</td>
</tr>
</tbody>
</table>

• Ideally values should be 90%
“Whole Image” RPC Fit Analysis

- Goal is to confirm that RPC support data provides comparable geolocation as Physical Sensor Model parameters
  - RPC parameters were fit to Physical Model by DigitalGlobe

- Methodology
  - 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 each of three elevation planes near ground
  - Determine the difference in horizontal ground coordinates at each grid location for each elevation plane
  - Estimate overall statistics, including maximum differences
Jomo Kenyatta, Kenya

More Nadir

More Off-Nadir

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Masirah Island, Oman

Height Plane: -521 m

Height Plane: -20 m

Height Plane: -519 m

Height Plane: -18 m

Height Plane: 481 m

Height Plane: 483 m

More Nadir

More Off-Nadir

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Maximum Differences between RPC and Physical Model Geolocation

Collection Date

Maximum Magnitude (m)


0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8

65 Stereo Mates
Ortho-Ready 2A Product Geolocation Consistency Results

- From first test set
  - 3 OR2A “stereo pairs” compared to corresponding Basic 1B stereo pairs
- Geolocation errors compared (ΔΔ)
- Differences are small

<table>
<thead>
<tr>
<th>Test Site</th>
<th>Basic 1B Product</th>
<th>Ortho-Ready 2A Product</th>
<th>Mono Mates</th>
<th>Stereo Pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>BO_El_Trompillo_Bolivia</td>
<td>14SEP08141129-P1BS-500167188010_01_P001</td>
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<td>-0.04</td>
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<td>-0.01</td>
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<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Summary

• Using 33 Basic 1B stereo pairs (2\textsuperscript{nd} dataset)…
  – Absolute geolocation accuracy estimated between 3.7-3.9 meters for HE90 and 2.7 m for VE90
  – Error propagation analyzed
  – RPC model geolocation is not exactly the same as the PM but is comparable

• From 1\textsuperscript{st} dataset
  – OR2A products have comparable geolocation to Basic 1B products
Backups
RPC Generation from Physical Model

Physical Sensor Model (e.g., Pushbroom):
line = f_1(X,Y,Z) and sample = f_2(X,Y,Z)
in terms of physical sensor model parameters

Used to generate…

RPC:
line = g_1(X,Y,Z) and sample = g_2(X,Y,Z)
in terms of rational polynomial coefficients
Note: Only applies within fit volume!

RPC is generated by DigitalGlobe

Grid of Points in Image

Fit Check Point
Fit Point

Z
X

Adapted from Figure 11.28 in Manual of Photogrammetry, 5th Edition, p. 889.

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Non-Parametric 90th Percentile Estimator for Ordered Statistics

Given \( n \) ordered data points \( x(1), x(2), \ldots, x(n) \), where
\[ x(i) = \Delta r(i) \text{ for HE90 and } x(i) = \text{abs}(\Delta h(i)) \text{ for VE90}. \]

\[ \text{HE90 or LE90} = (1 - f)^* x(i) + f^* x(i+1) \]

with
\[ i = \text{integer part of } 0.9*n + 0.5, \text{ and} \]
\[ f = \text{fractional part of } 0.9*n + 0.5. \]
Confidence Statements for Non-Parametric CE90/LE90

• Given independent and identically-distributed data points $X_1, X_2, \ldots, X_n$
• Ordered data points are $X_{(1)}, X_{(2)}, \ldots, X_{(n)}$ for $n$ data points
• Probability that actual CE90 (or LE90) $\leq$ a given $k^{th}$ ordered data point is at least the value given by binomial distribution, i.e.,

$$P(x_{0.9} \leq X_{(k)}) \geq \sum_{i=0}^{k-1} \binom{n}{i} (0.9)^i (1 - 0.9)^{n-i}$$

• Confidence statement for every ordered data point
• Does not depend upon parent population distribution

Fictitious Example (Confidence)

Given an ordered sample set as follows (n=25):

\[
X_{(1)}=14.1, \ X_{(2)}=14.5, \ X_{(3)}=14.6, \ X_{(4)}=14.7, \ X_{(5)}=14.8, \ X_{(6)}=15.3,
\]

\[
X_{(7)}=15.4, \ X_{(8)}=15.6, \ X_{(9)}=15.7, \ X_{(10)}=16.0, \ X_{(11)}=16.1,
\]

\[
X_{(12)}=16.1, \ X_{(13)}=16.2, \ X_{(14)}=16.5, \ X_{(15)}=16.7, \ X_{(16)}=16.8,
\]

\[
X_{(17)}=17.1, \ X_{(18)}=17.1, \ X_{(19)}=17.3, \ X_{(20)}=17.7, \ X_{(21)}=17.8,
\]

\[
X_{(22)}=17.9, \ X_{(23)}=18.3, \ X_{(24)}=18.6, \ X_{(25)}=20.1
\]

Estimated HE90 (or VE90) is \(X_{(23)}\) data point (18.3)

A statement can be made for each ordered data point: \(x_{(k)}\):

- The confidence that actual CE90 (or LE90) ≤ the value 17.7 is ≥ 3%.
- The confidence that actual CE90 (or LE90) ≤ the value 17.8 is ≥ 10%.
- The confidence that actual CE90 (or LE90) ≤ the value 17.9 is ≥ 24%.
- The confidence that actual CE90 (or LE90) ≤ the value 18.3 is ≥ 46%.
- The confidence that actual CE90 (or LE90) ≤ the value 18.6 is ≥ 73%.
- The confidence that actual CE90 (or LE90) ≤ the value 20.1 is ≥ 93%.
WV03 Basic 1B Mono Geolocation Accuracy (More Off-Nadir Mates)

Basic 1B CSM HE90 = 4.2m

RPC HE90 = 4.0m

Basic 1B CSM Mean: (-0.8m, -0.9m)
RPC Mean: (-0.7m, -0.5m)