WorldView-3 Geolocation Accuracy and Band Co-Registration Analysis

Paul Bresnahan*, Dr. Robert Powers*, and Luis HenryVazquez

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* Contractors supporting NGA

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Outline

Background

Methodology

Results

DigitalGlobe WorldView-3 Satellite

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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)

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

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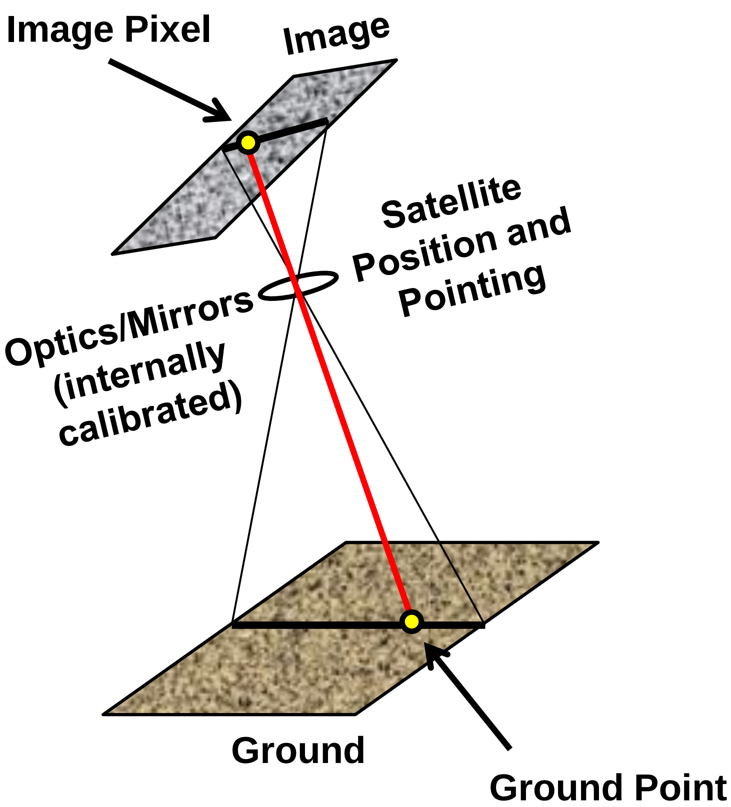
Physical Sensor Model (PM)



- 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)

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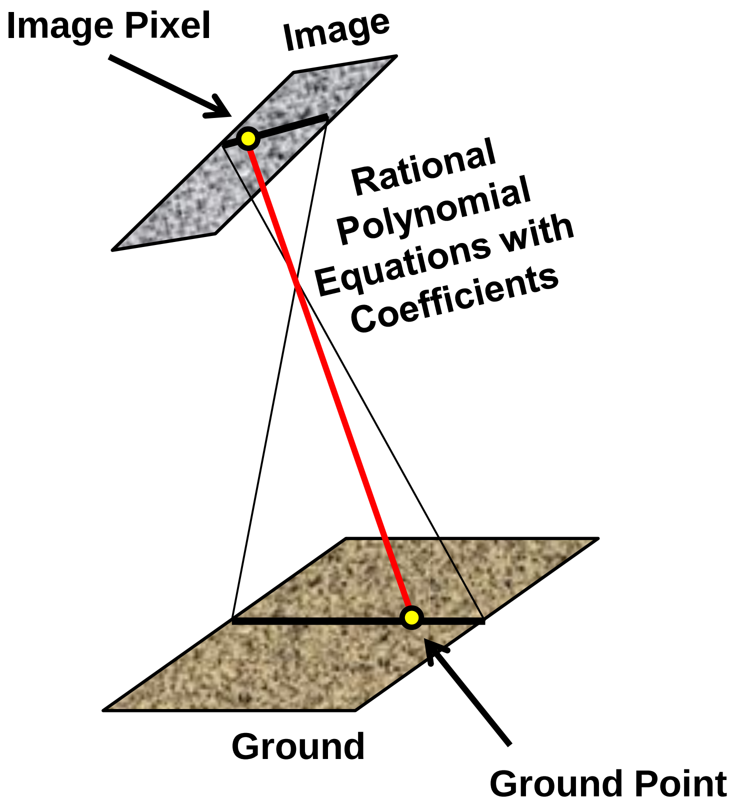
Rational Polynomial Coefficients (RPC) Model



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

image row = f_1(lat,long,height)
image column = f_2(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

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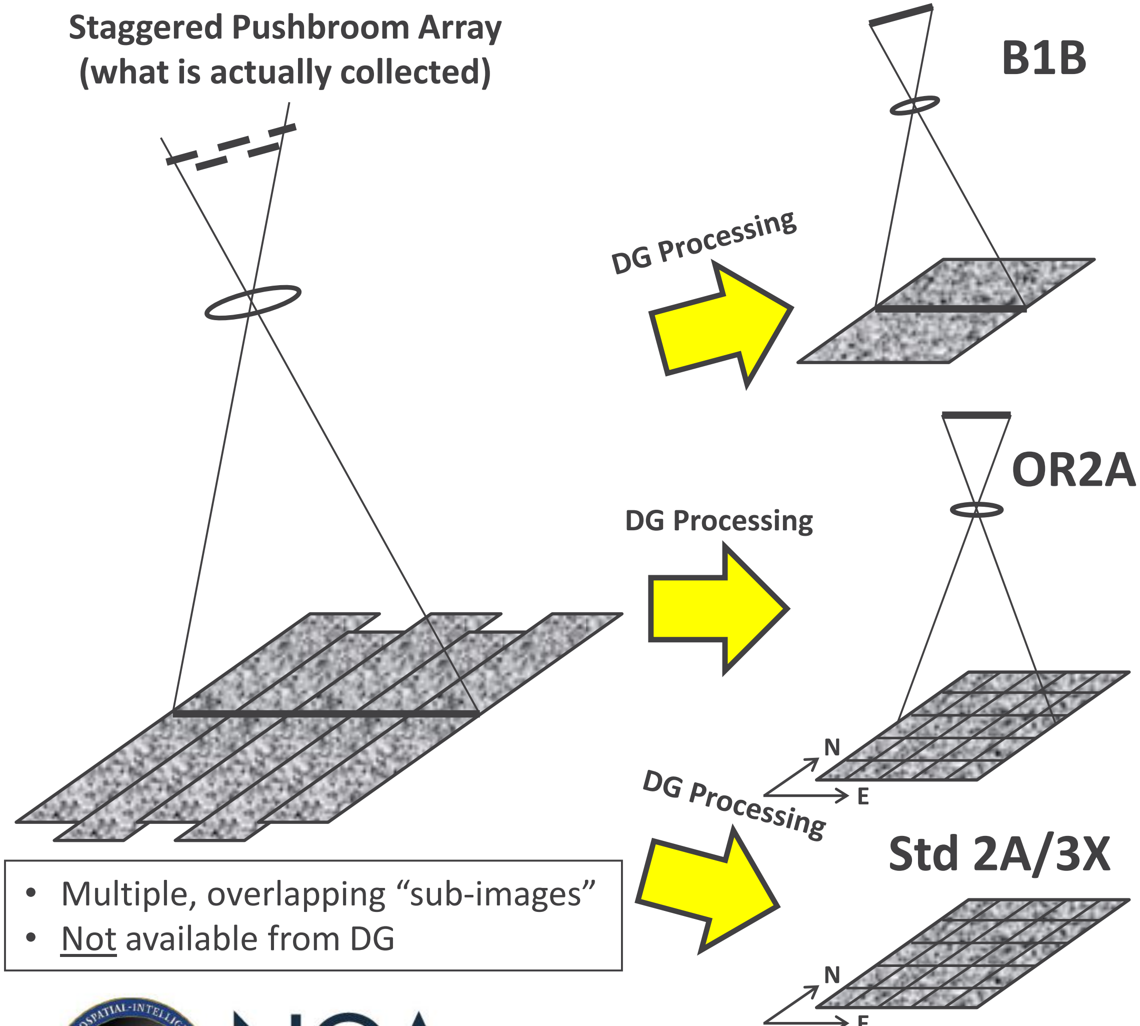
Geometry of DigitalGlobe Product Processing



- 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

Test	WorldView-3			
	Pan	MSI	SWIR	CAVIS
Absolute Geolocation Accuracy ("How close to true geolocation?")	B1B	B1B	B1B	
Error Propagation ("How realistic is accuracy prediction?")	B1B	B1B	B1B	
Band-to-Band Co-registration ("How well do bands align within image?")			B1B, OR2A	B1B, OR2A, 2A
Sensor Co-registration ("How well do co-boresighted images align?"	B1B	B1B	B1B	
RPC Fit to Physical Model ("RPC- vs. PM-derived coordinates")	B1B	B1B	B1B	

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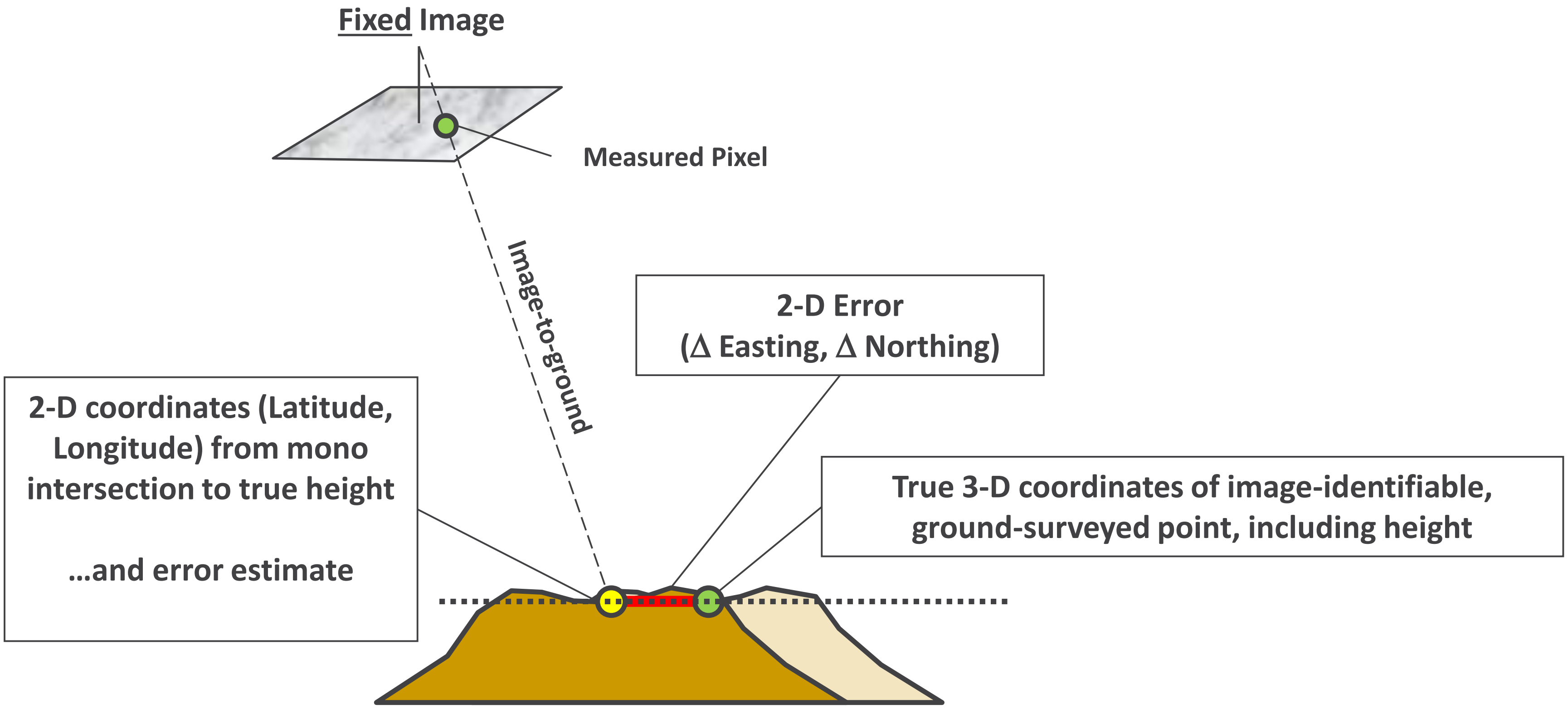
Absolute Geolocation Accuracy, Error Propagation, Sensor Co-registration, and RPC Fit Analysis – Mono Intersection



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

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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 x 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, Δr, and standard deviation of the errors over all *N n x n* samples

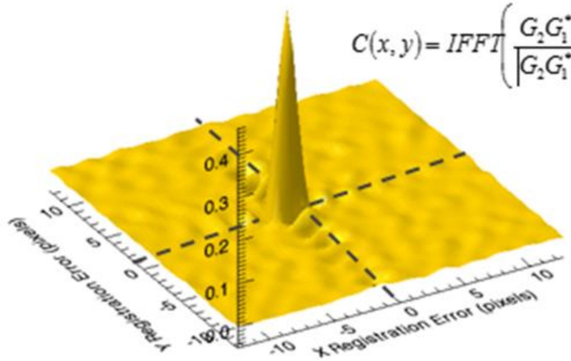
For image bands g_1 & g_2, the Fourier Transforms are:

$$g_1(x,y) \qquad FFT(g_1) = G_1(u,v)$$

$$g_2(x,y) = g_1(x+x_0, y+y_0) \qquad FFT(g_2) = FFT(g_1(x+x_0, y+y_0)) = G_1(u,v)e^{-j(u*x_0+v*y_0)}$$

The correlation surface is $C(x,y)$, *where the maximum estimates the point of registration to pixel accuracy,* Δx *and* Δy

$$C(x,y) = IFFT\left(\frac{G_2 G_1^*}{|G_2 G_1^*|}\right) = IFFT\left(e^{-j(ux_0+vy_0)}\right)$$



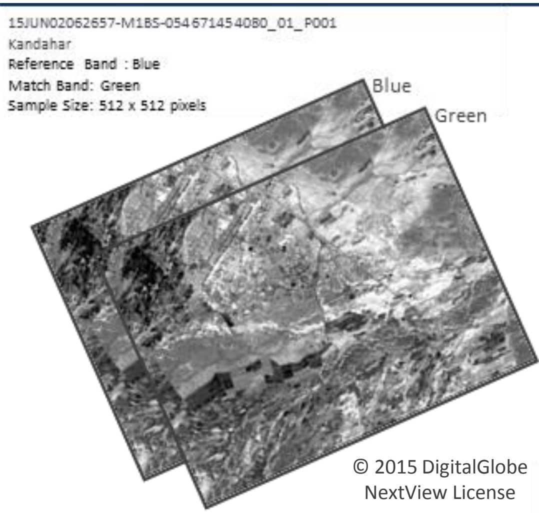
Sub-pixel error estimates δx and δy are determined by calculating the center of mass of a 5 x 5 window centered on the main peak [6]

$$\delta x = \frac{\left(\sum_{i=0}^{4} C_{ij}\right)\cdot[i_i]_{0,4}}{\sum C_{i,j}} - 2 \qquad \Delta X = \Delta x + \delta x$$

$$\delta y = \frac{\left(\sum_{i=0}^{4} C_{ij}\right)^T\cdot[i_i]_{0,4}}{\sum C_{i,j}} - 2 \qquad \Delta Y = \Delta y + \delta y$$

$$\Delta r = \sqrt{\Delta X^2 + \Delta Y^2}$$

Example Co-Registration Accuracy Measurement GeoEye-1 MSI Image: Green Band Relative to Blue Band



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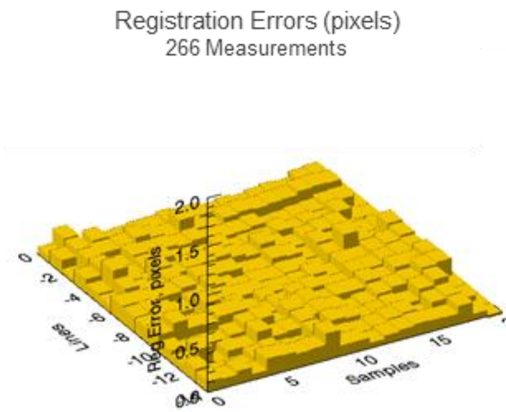

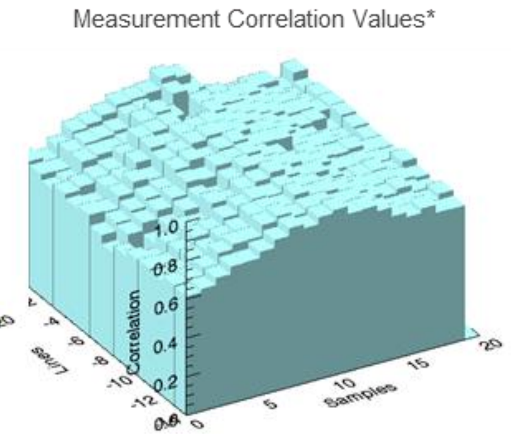

Summary of Image Measurement Statistics	
Mean Reg Error (pixels):	0.115
Standard Dev (pixels):	0.062
Median Reg Error (pixels):	0.106
Max Reg Error (pixels):	0.293
Min Reg Error(pixels):	0.004

Magnitude of Registration Error (pixels)

Measurment Sample Size: 512 x 512 pixels

Line	Sample																		
	1	512	1023	1534	2045	2556	3067	3578	4089	4600	5111	5622	6133	6644	7155	7666	8177	8688	9199
1	0.068	0.215	0.028	0.114	0.043	0.053	0.070	0.072	0.101	0.079	0.078	0.044	0.070	0.052	0.076	0.094	0.081	0.147	0.163
512	0.133	0.201	0.095	0.094	0.110	0.159	0.122	0.089	0.217	0.086	0.047	0.117	0.136	0.124	0.138	0.146	0.184	0.193	0.186
1023	0.045	0.196	0.029	0.035	0.122	0.105	0.111	0.088	0.109	0.065	0.065	0.069	0.090	0.032	0.042	0.062	0.075	0.114	0.120
1534	0.143	0.216	0.037	0.042	0.104	0.146	0.076	0.061	0.042	0.102	0.027	0.044	0.049	0.104	0.056	0.093	0.068	0.138	0.015
2045	0.096	0.293	0.144	0.052	0.191	0.089	0.119	0.123	0.141	0.097	0.064	0.151	0.092	0.039	0.094	0.129	0.146	0.030	0.012
2556	0.078	0.205	0.136	0.127	0.171	0.045	0.114	0.105	0.098	0.031	0.026	0.106	0.092	0.016	0.146	0.096	0.144	0.127	0.142
3067	0.175	0.166	0.156	0.160	0.195	0.049	0.132	0.069	0.024	0.047	0.039	0.059	0.054	0.004	0.125	0.291	0.191	0.123	0.282
3578	0.161	0.174	0.123	0.087	0.146	0.053	0.105	0.085	0.082	0.038	0.037	0.050	0.101	0.051	0.142	0.137	0.185	0.222	0.262
4089	0.153	0.195	0.076	0.046	0.245	0.100	0.122	0.028	0.108	0.020	0.078	0.106	0.073	0.047	0.145	0.153	0.189	0.214	0.239
4600	0.184	0.264	0.170	0.158	0.206	0.210	0.178	0.109	0.149	0.101	0.124	0.065	0.099	0.100	0.161	0.133	0.218	0.217	0.284
5111	0.123	0.073	0.082	0.079	0.118	0.182	0.204	0.093	0.208	0.099	0.122	0.103	0.033	0.064	0.129	0.160	0.181	0.274	0.292
5622	0.083	0.199	0.008	0.099	0.082	0.210	0.122	0.135	0.200	0.027	0.122	0.105	0.053	0.072	0.105	0.088	0.199	0.255	0.119
6133	0.138	0.028	0.017	0.026	0.095	0.121	0.070	0.061	0.189	0.064	0.068	0.059	0.082	0.117	0.138	0.052	0.165	0.193	0.119
6644	0.114	0.099	0.137	0.063	0.180	0.172	0.148	0.157	0.274	0.109	0.111	0.056	0.088	0.105	0.123	0.116	0.110	0.187	0.066

*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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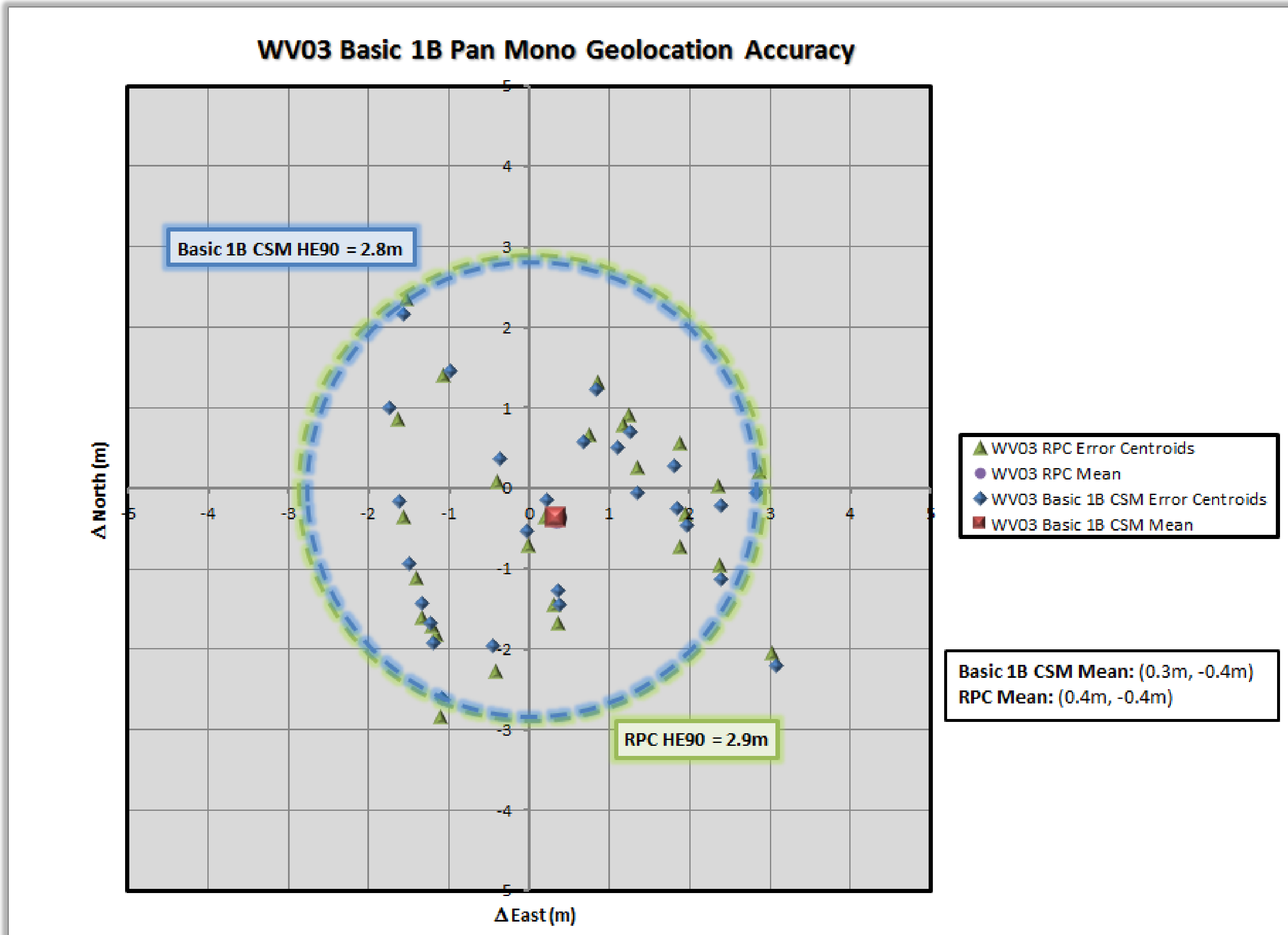
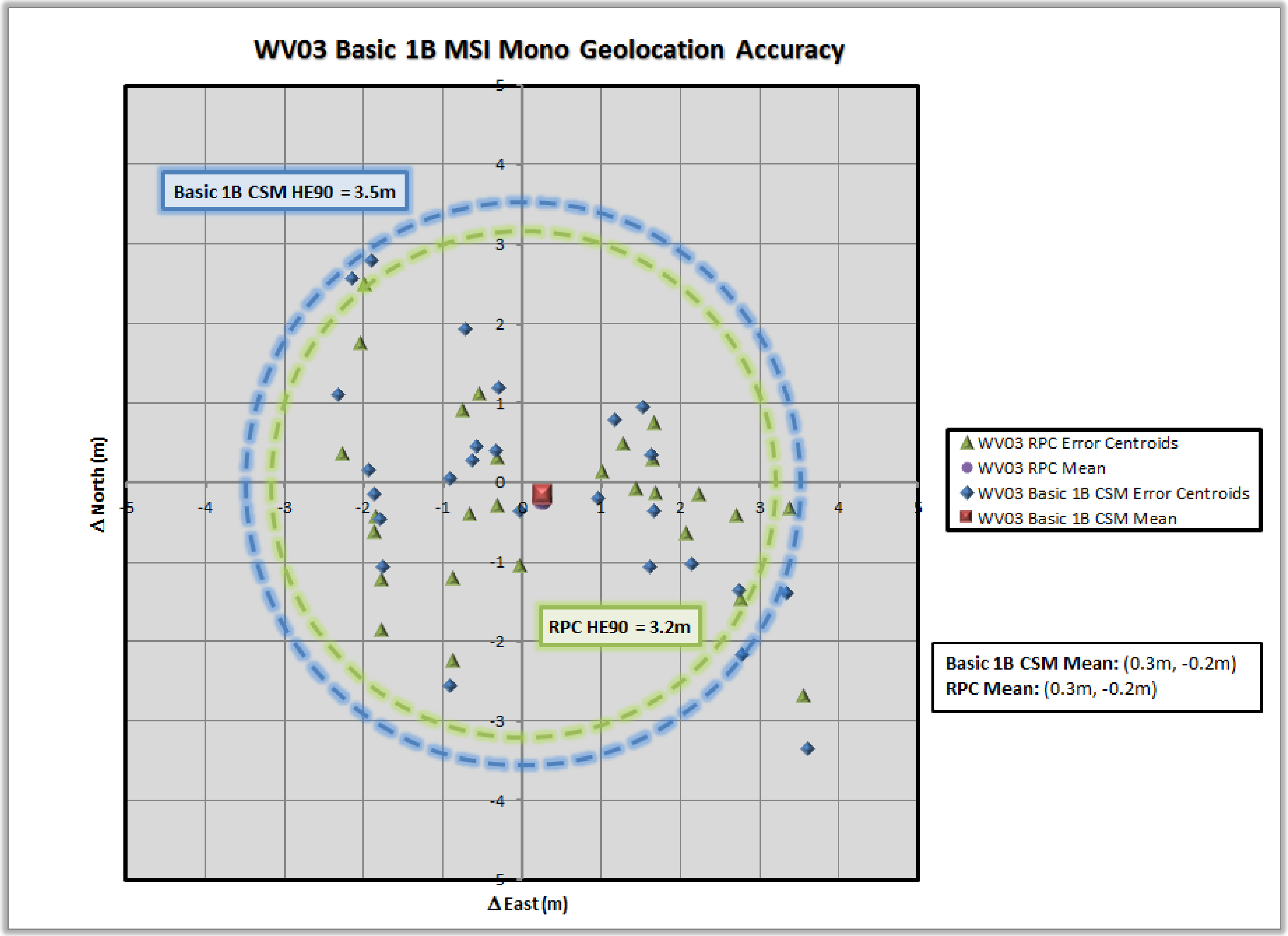
WV03 Absolute Geolocation Accuracy Results

Using no Ground Control Points

Sample size of 27 WorldView-3 Basic 1B Mono Images (Physical Model)			
	Sample Mono HE90 (m)	Confidence Statements	Nominal Nadir Pixels
Panchromatic	2.8	> 94% confidence that True CE90 < 3.8m	9.0
8-Band MSI	3.5	> 94% confidence that True CE90 < 5.0m	2.8
8-Band SWIR	5.9	> 94% confidence that True LE90 < 7.6m	1.6

Sample size of 27 WorldView-3 Basic 1B Mono Images (RPC)			
	Sample Mono HE90 (m)	Confidence Statements	Nominal Nadir Pixels
Panchromatic	2.9	> 94% confidence that True CE90 < 3.7m	9.4
8-Band MSI	3.2	> 94% confidence that True CE90 < 4.5m	2.6
8-Band SWIR	4.6	> 94% confidence that True LE90 < 6.1m	1.2


WV03 Basic 1B Pan Mono Geolocation Accuracy
Basic 1B CSM HE90 = 2.8m
RPC HE90 = 2.9m
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)



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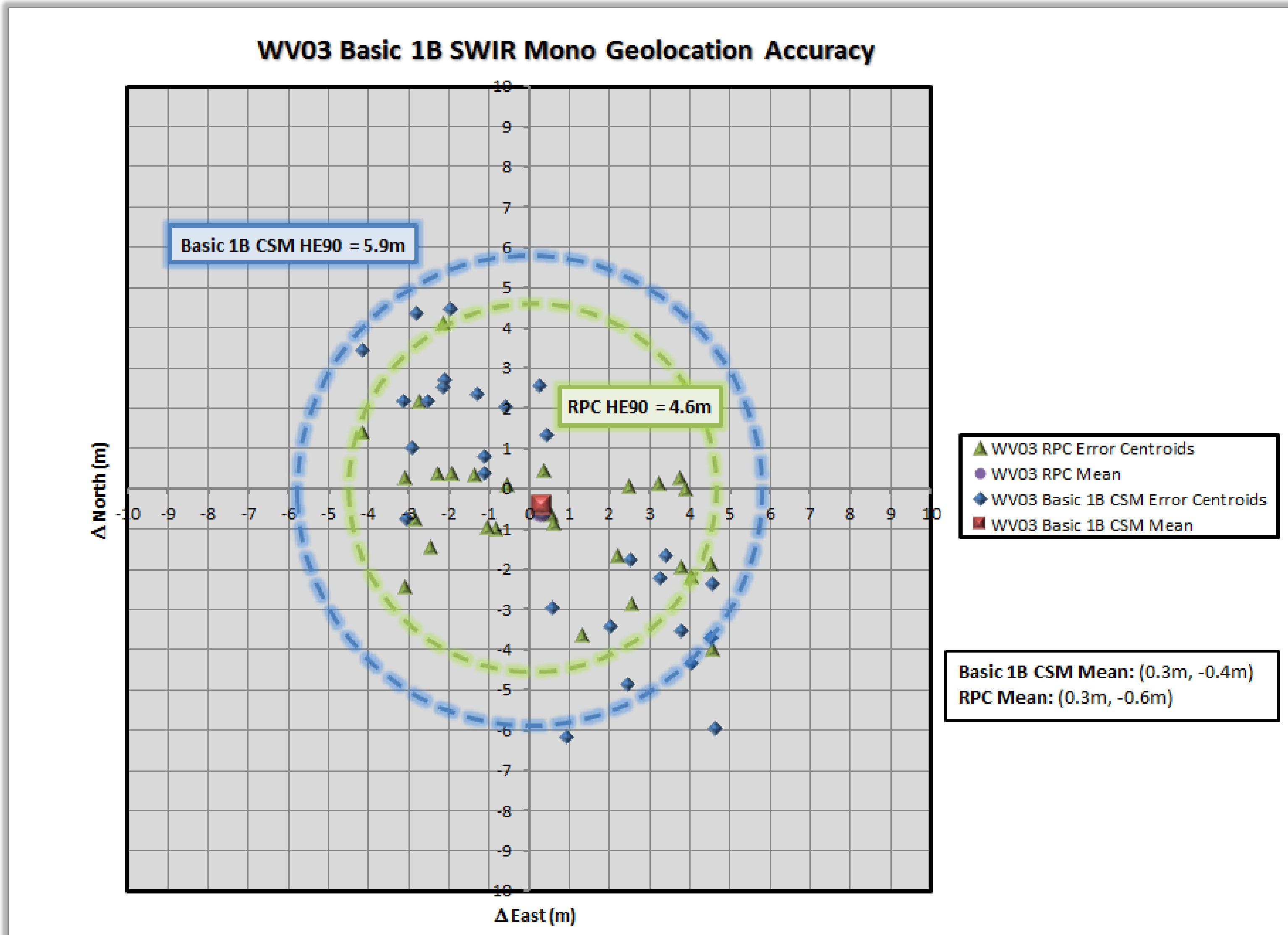

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Error Propagation Analysis

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

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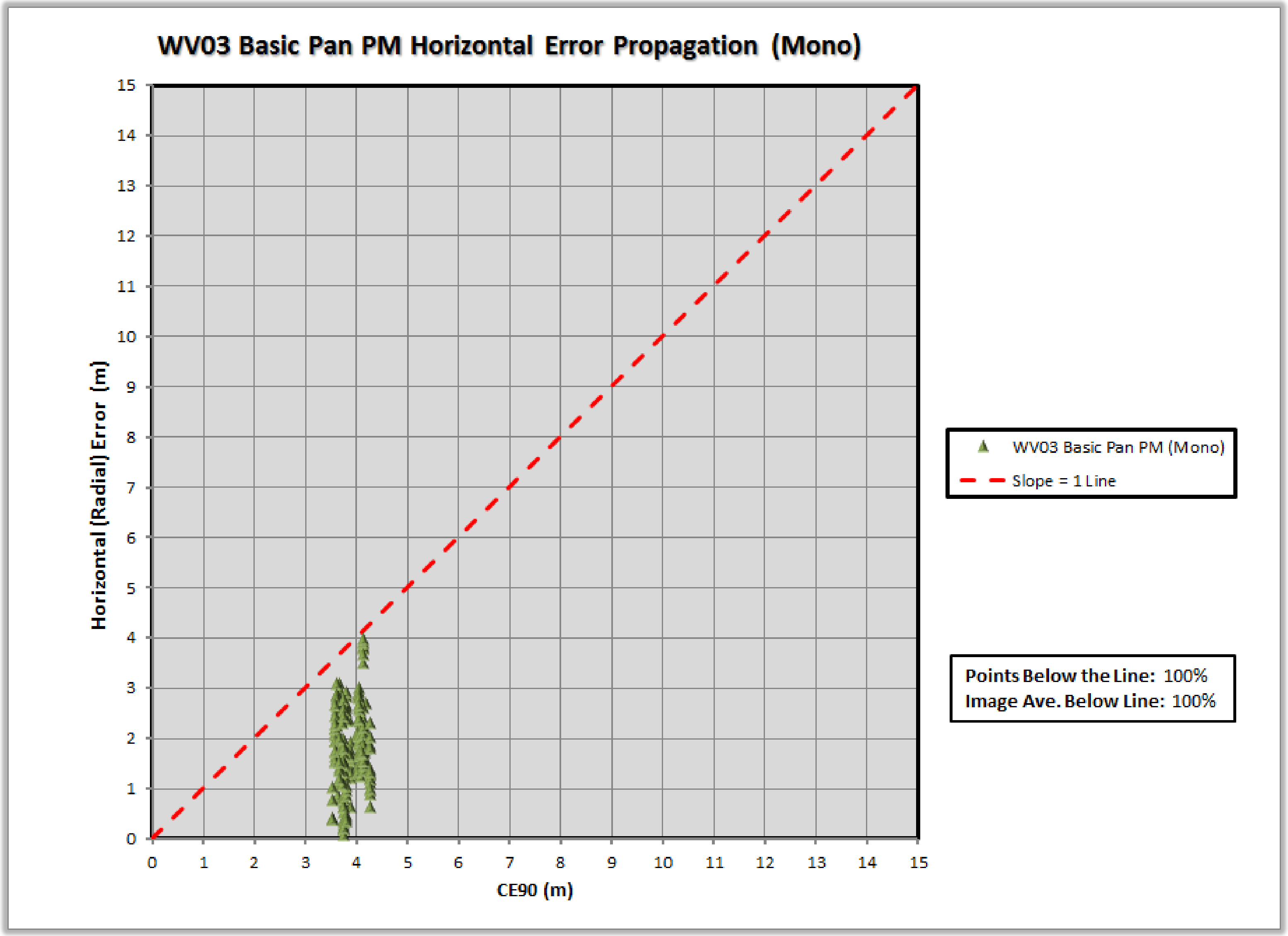

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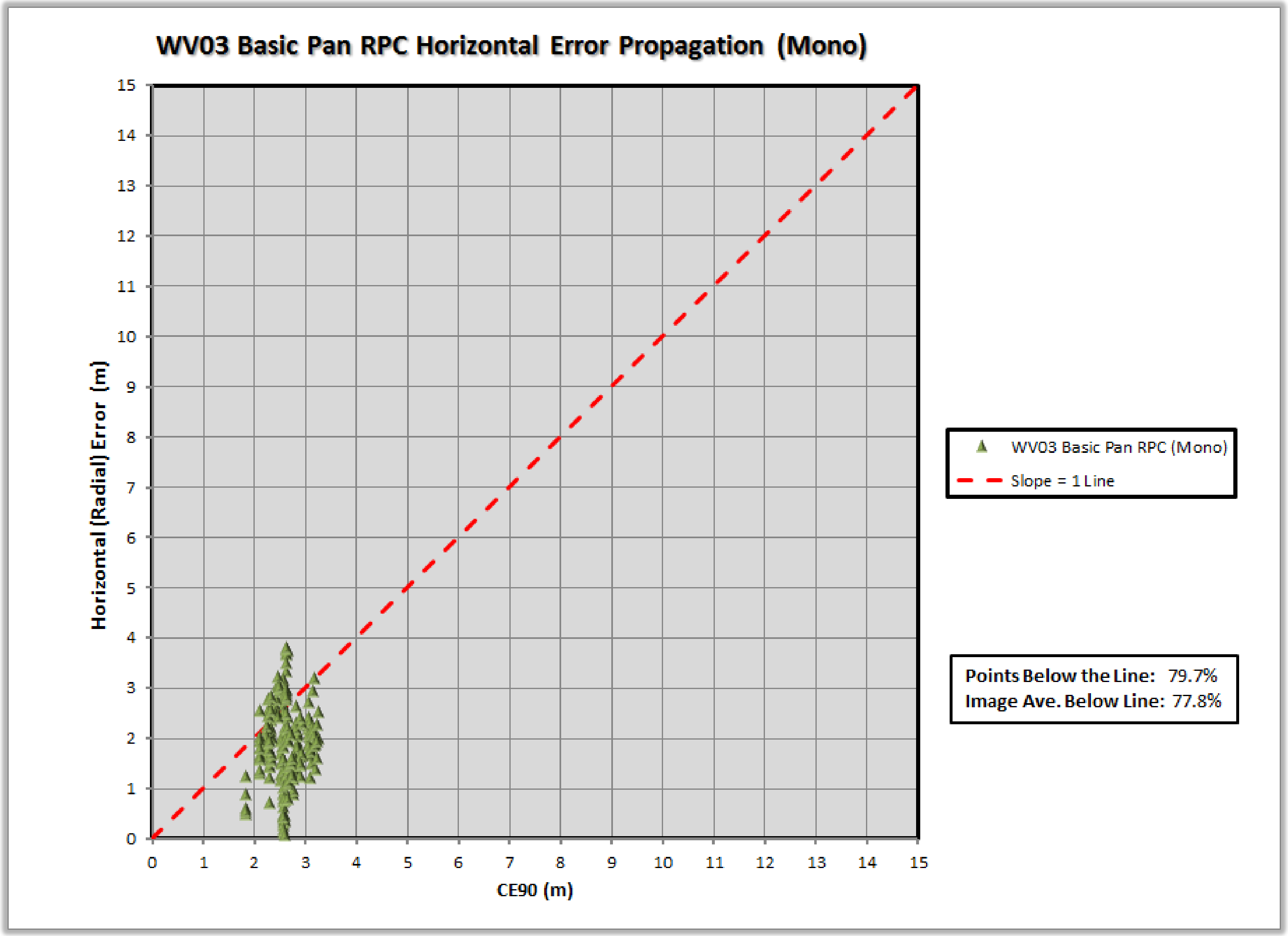

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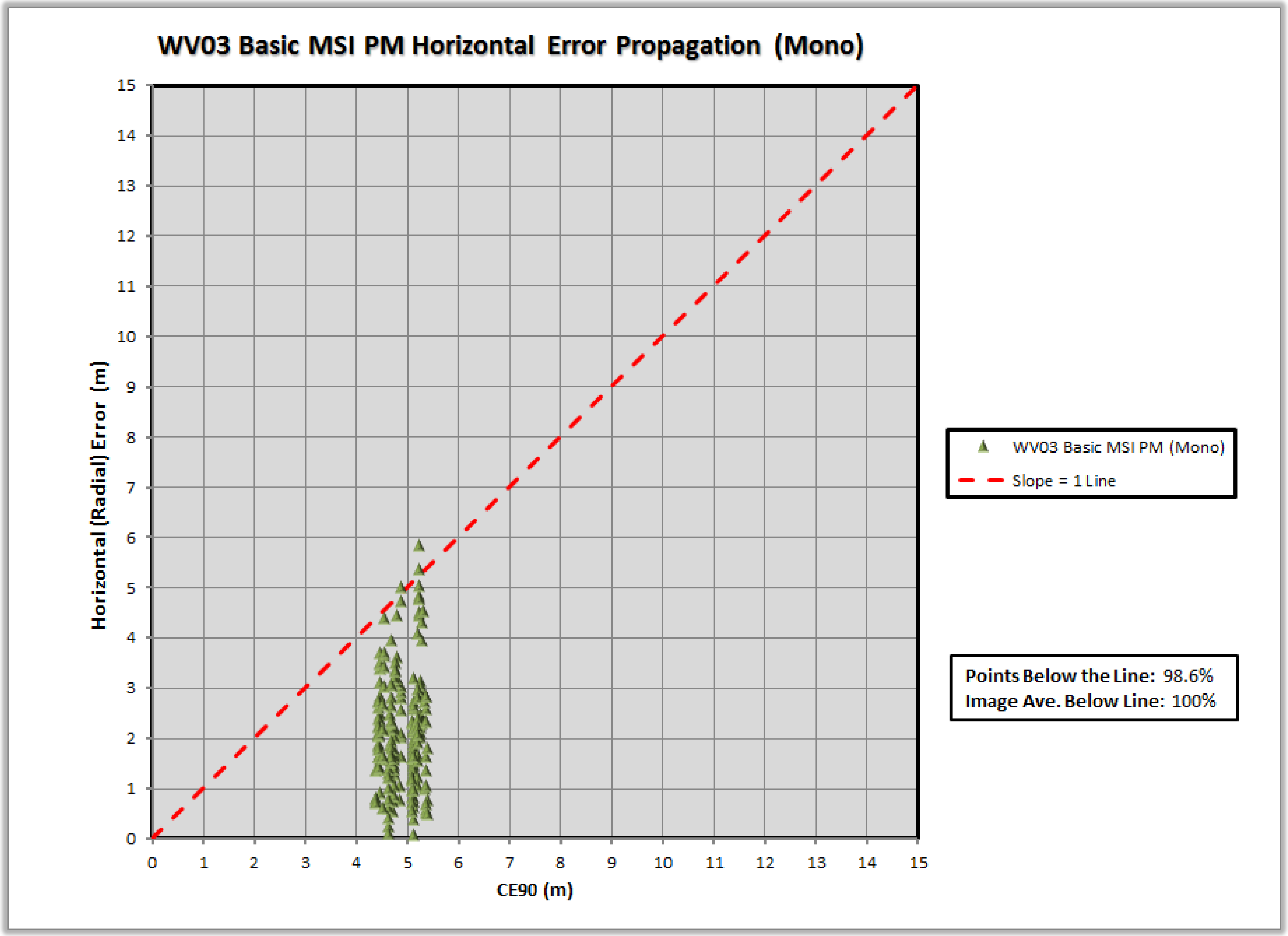

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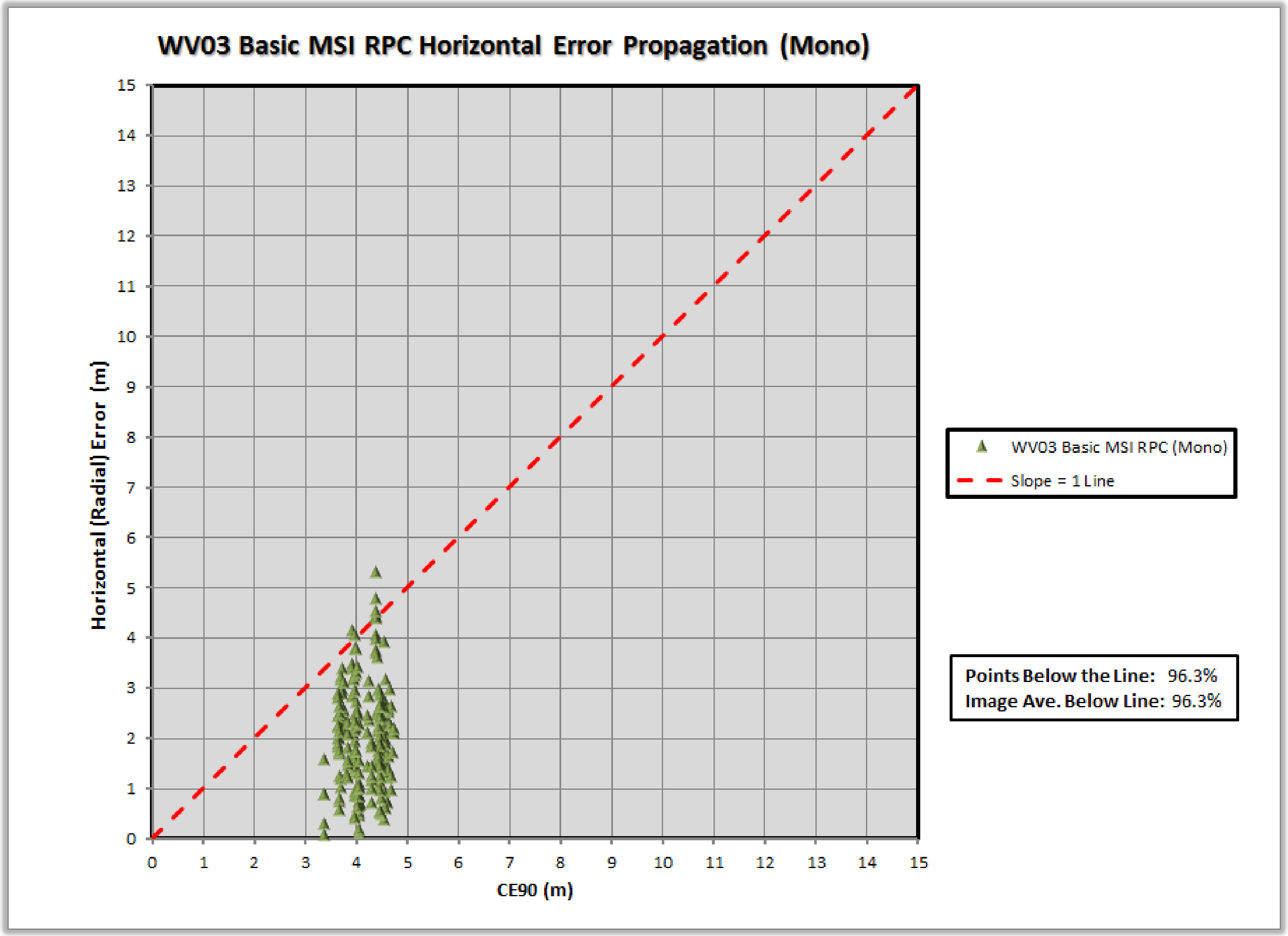

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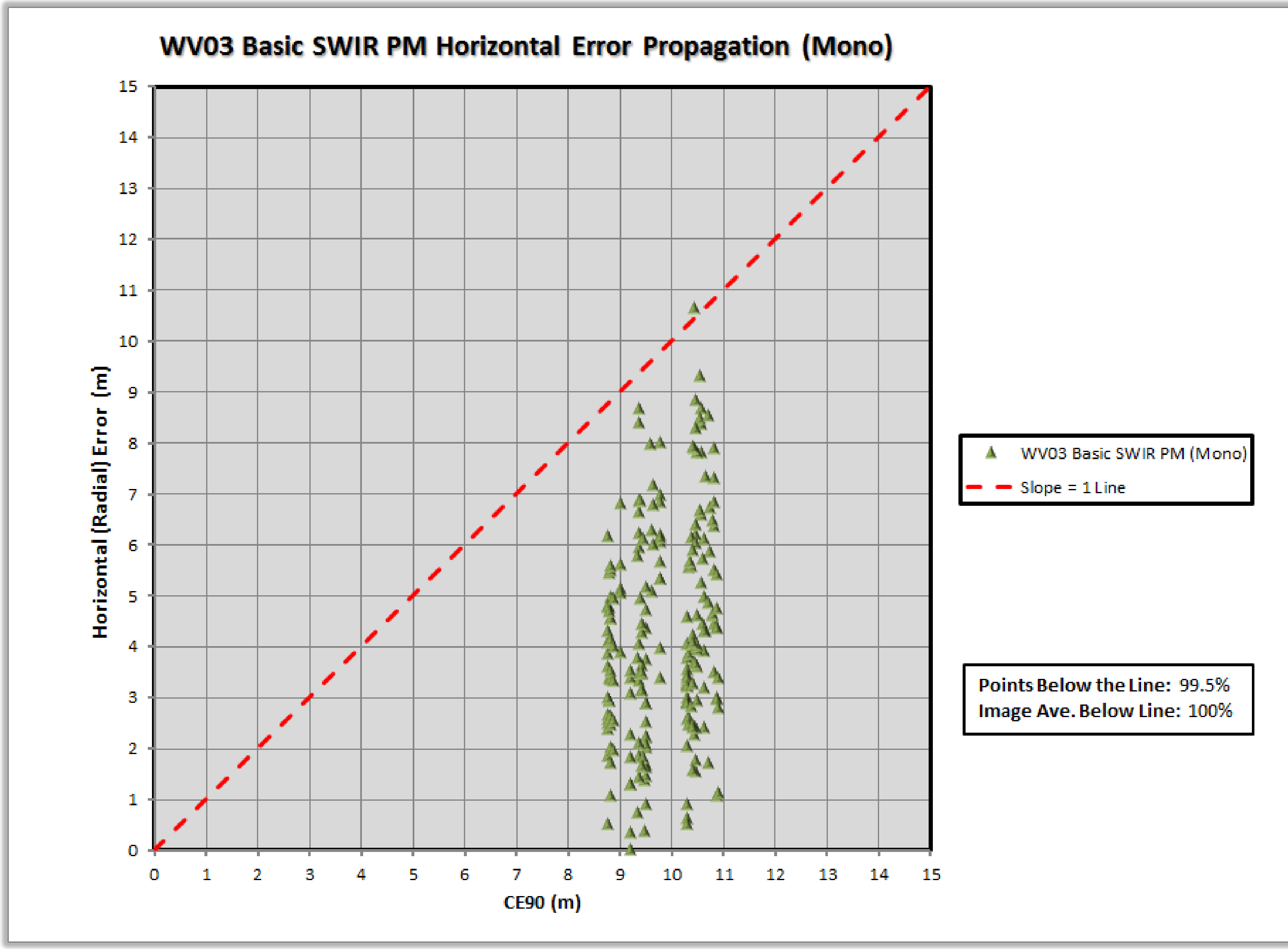
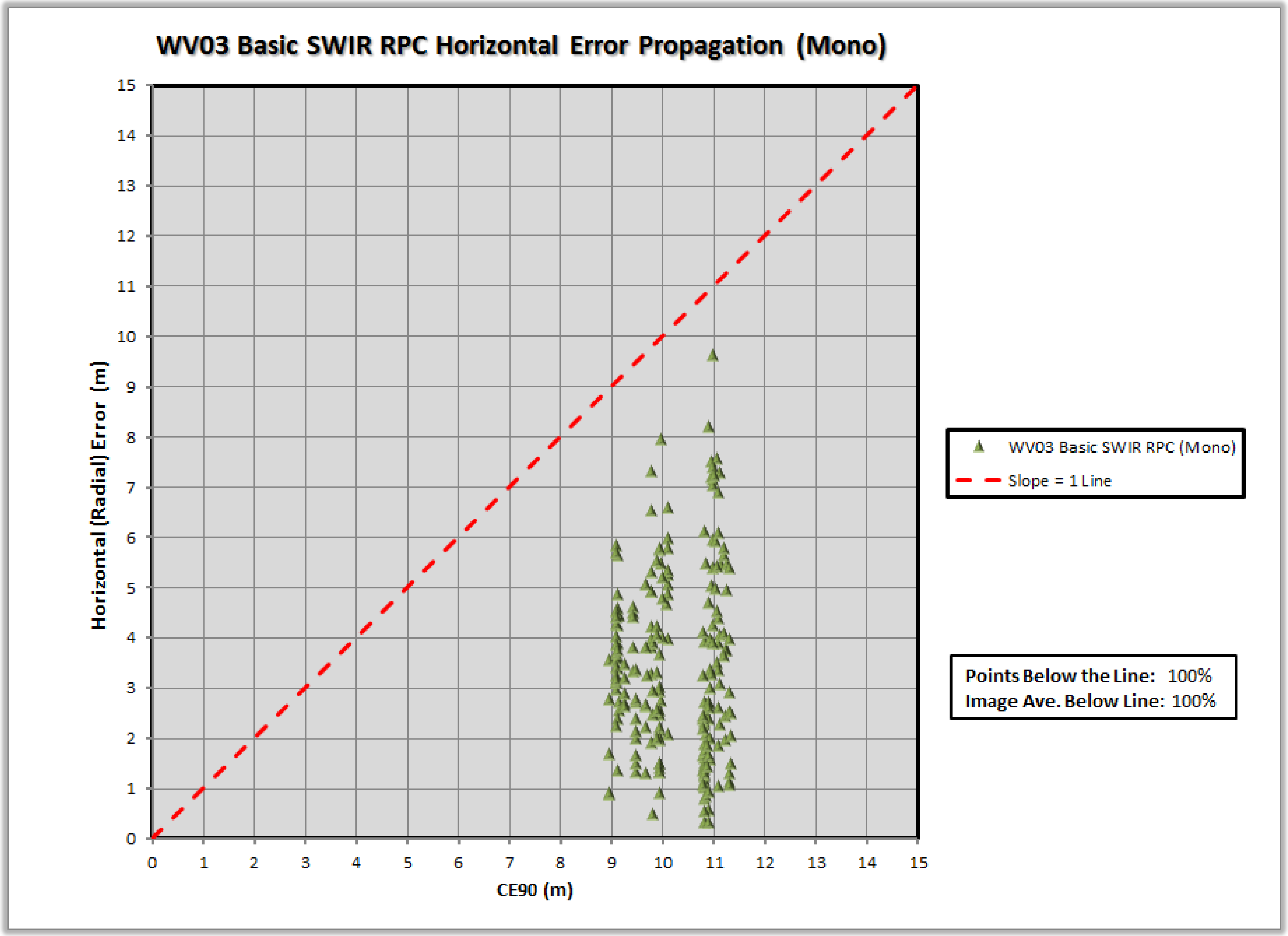


WV03 Basic SWIR PM Horizontal Error Propagation (Mono)
Horizontal (Radial) Error (m)
CE90 (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
WV03 Basic SWIR PM (Mono)
Slope = 1 Line
Points Below the Line: 99.5%
Image Ave. Below Line: 100%



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WV03 Error Propagation Summary

Error Propagation (% Below Slope = 1 Line)		
All 217 Points	Physical Model	RPC
Panchromatic	100.0%	79.7%
8-Band MSI	98.6%	96.3%
8-Band SWIR	99.5%	100.0%

Error Propagation (% Below Slope = 1 Line)		
Based on Ave for 27 Images	Physical Model	RPC
Panchromatic	100.0%	77.8%
8-Band MSI	100.0%	96.3%
8-Band SWIR	100.0%	100.0%

- 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

	Physical Model RMSE	RPC RMSE
MSI - Pan	1.6 m (1.3 pixels)	1.2 m (0.9 pixels)
SWIR - Pan	4.3 m (1.2 pixels)	3.3 m (0.9 pixels)
SWIR - MSI	3.3 m (0.9 pixels)	2.7 m (0.7 pixels)

RPC Fit Analysis

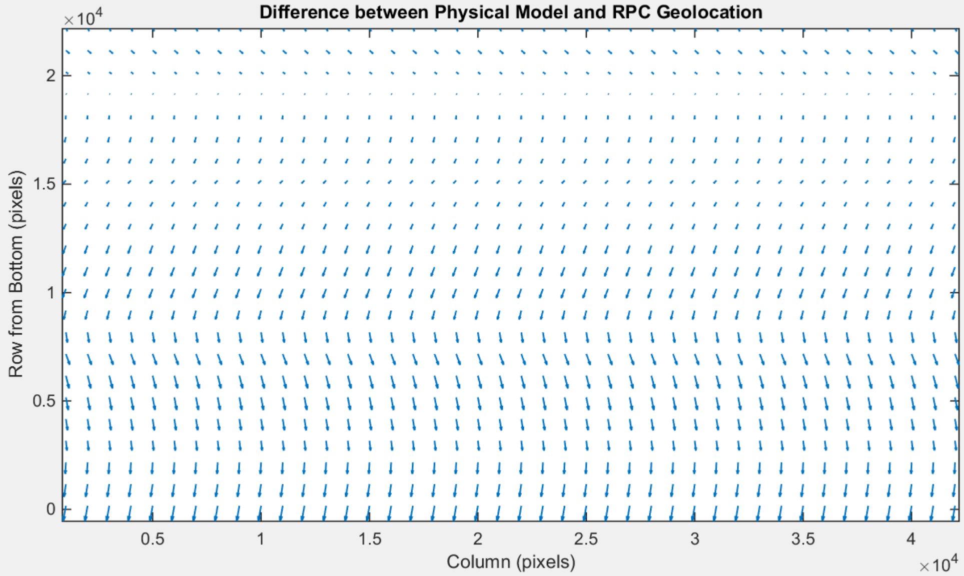
Goal is to confirm that RPC data provides comparable geolocation as Physical Sensor Model data

- 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: Keetsmanshoop, Namibia (WV03 Pan)



NA-Keetsmanshoop-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.)

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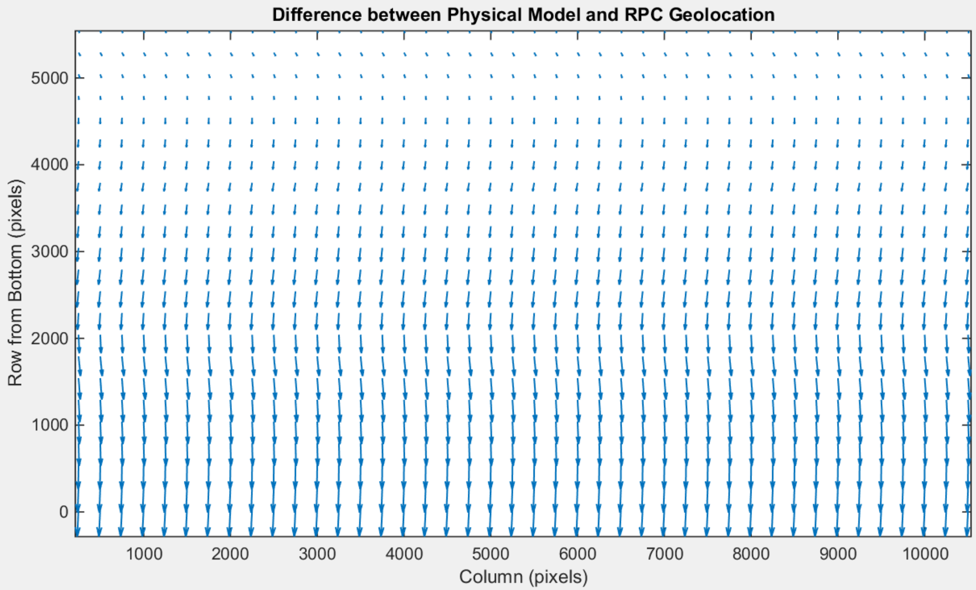
Example Plot: Keetsmanshoop, Namibia (WV03 MSI)



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.)

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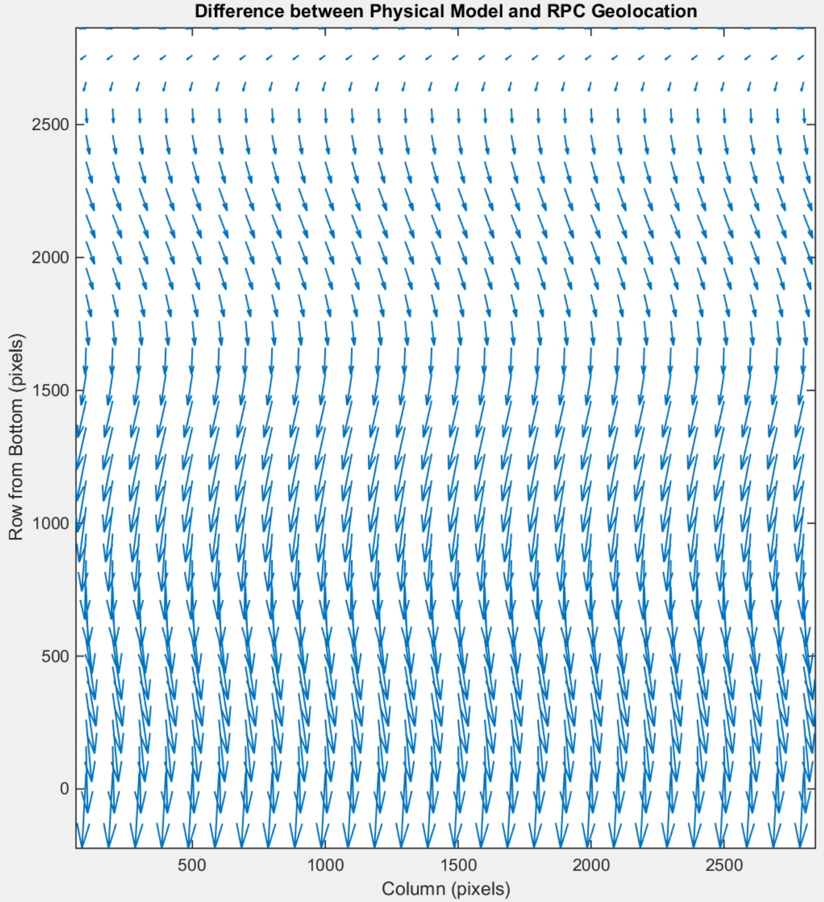
Example Plot: Keetsmanshoop, Namibia (WV03 SWIR)



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

Height Plane: 1036 m

Easting/Northing 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.)

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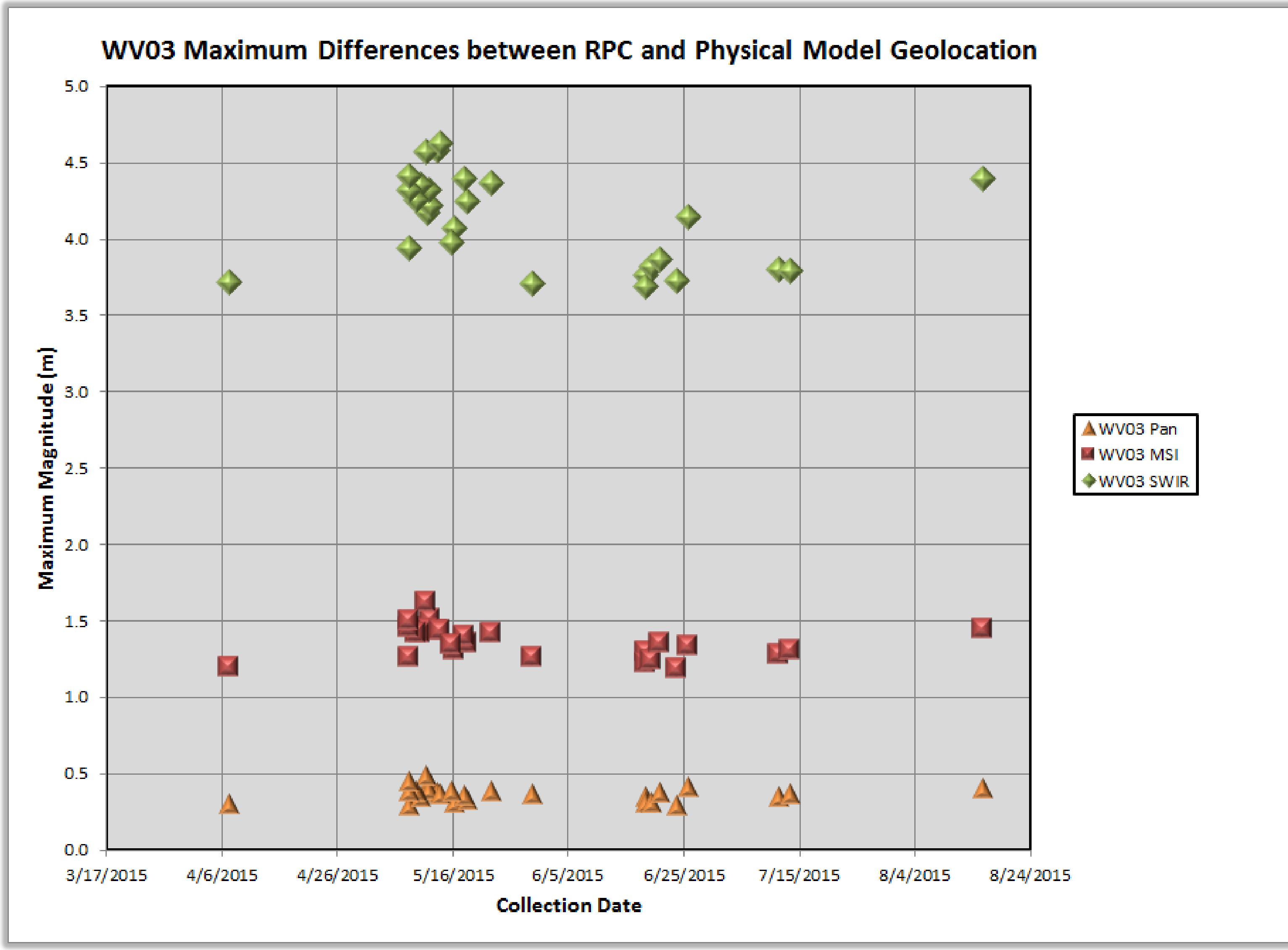

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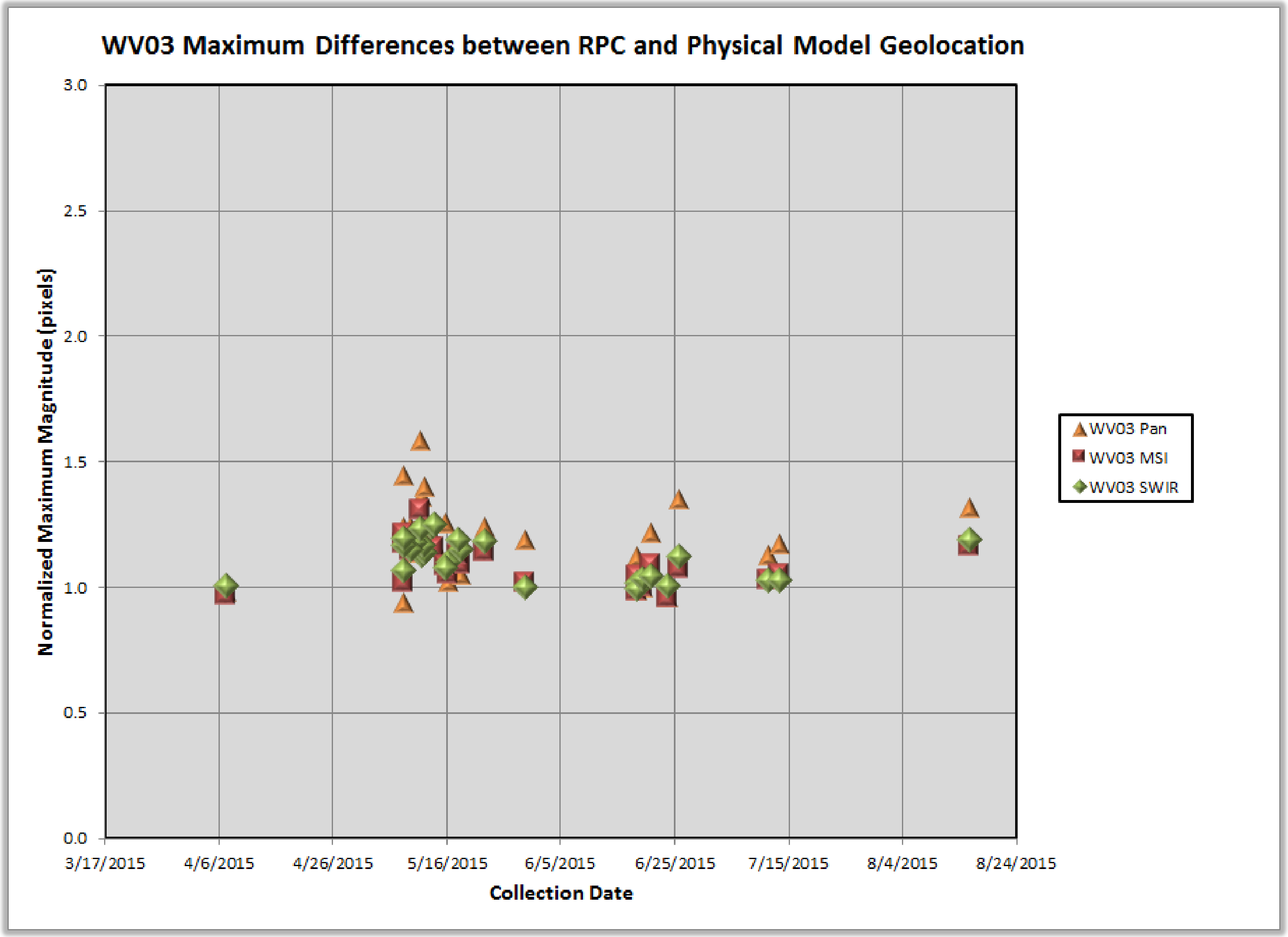

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WorldView-3 Band Co-Registration Results

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

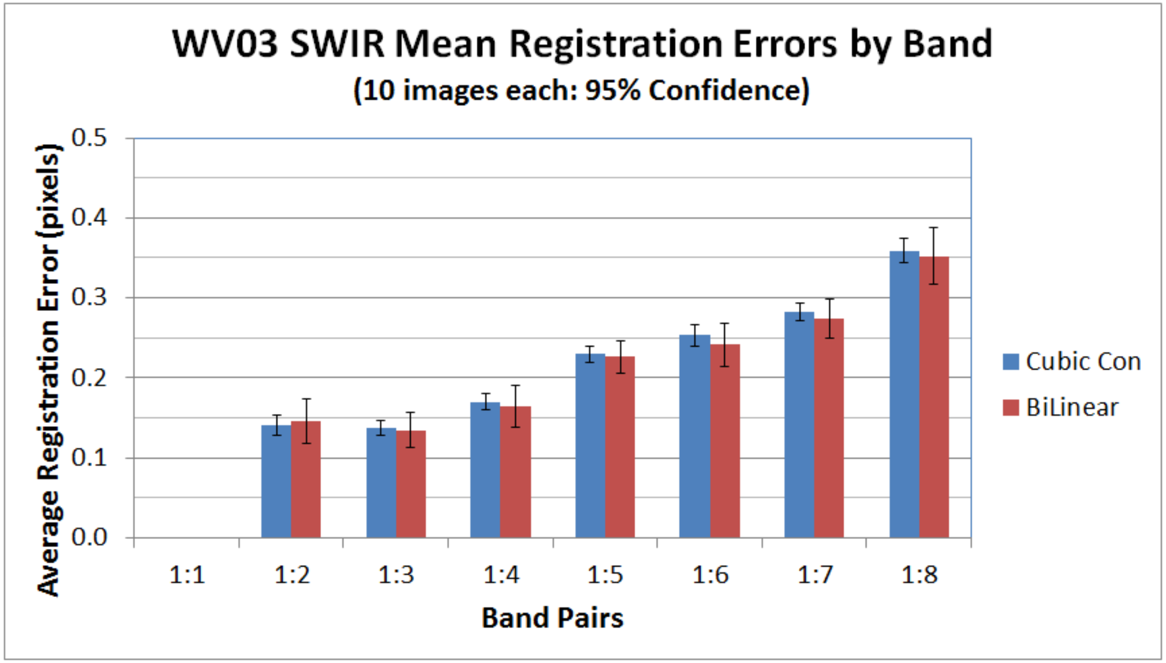
WorldView-3 SWIR Basic 1B/OR2A Band Co-Registration Results

Bilinear

#	IID
1	15MAY13190613-A1BS-500407394180_01_P001
2	15MAY29181947-A1BS-500407394210_01_P001
3	15MAY09150432-A1BS-500407394300_01_P001
4	15MAY14111559-A1BS-500407396180_01_P001
5	15MAY11091051-A1BS-500407396210_01_P001
6	15JUN23181534-A1BS-500407397120_01_P001
7	15JUL11113210-A1BS-500407397150_01_P001
8	15JUN18090806-A1BS-500407397240_01_P001
9a	15JUN25184605-A2AS_R1C1-500407485120_01_P001
9b	15JUN25184605-A2AS_R2C1-500407485120_01_P001
10	15AUG26090540-A2AS-500407485150_01_P001

Cubic Convolution

#	IID
1	15MAY13190613-A1BS-500407394170_01_P001
2	15MAY29181947-A1BS-500407394200_01_P001
3	15MAY09150432-A1BS-500407394290_01_P001
4	15MAY14111559-A1BS-500407396170_01_P001
5	15MAY11091051-A1BS-500407396200_01_P001
6	15JUN23181534-A1BS-500407397110_01_P001
7	15JUL11113210-A1BS-500407397140_01_P001
8	15JUN18090806-A1BS-500407397230_01_P001
9a	15JUN25184605-A2AS_R1C1-500407485110_01_P001
9b	15JUN25184605-A2AS_R2C1-500407485110_01_P001
10	15AUG26090540-A2AS-500407485140_01_P001



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

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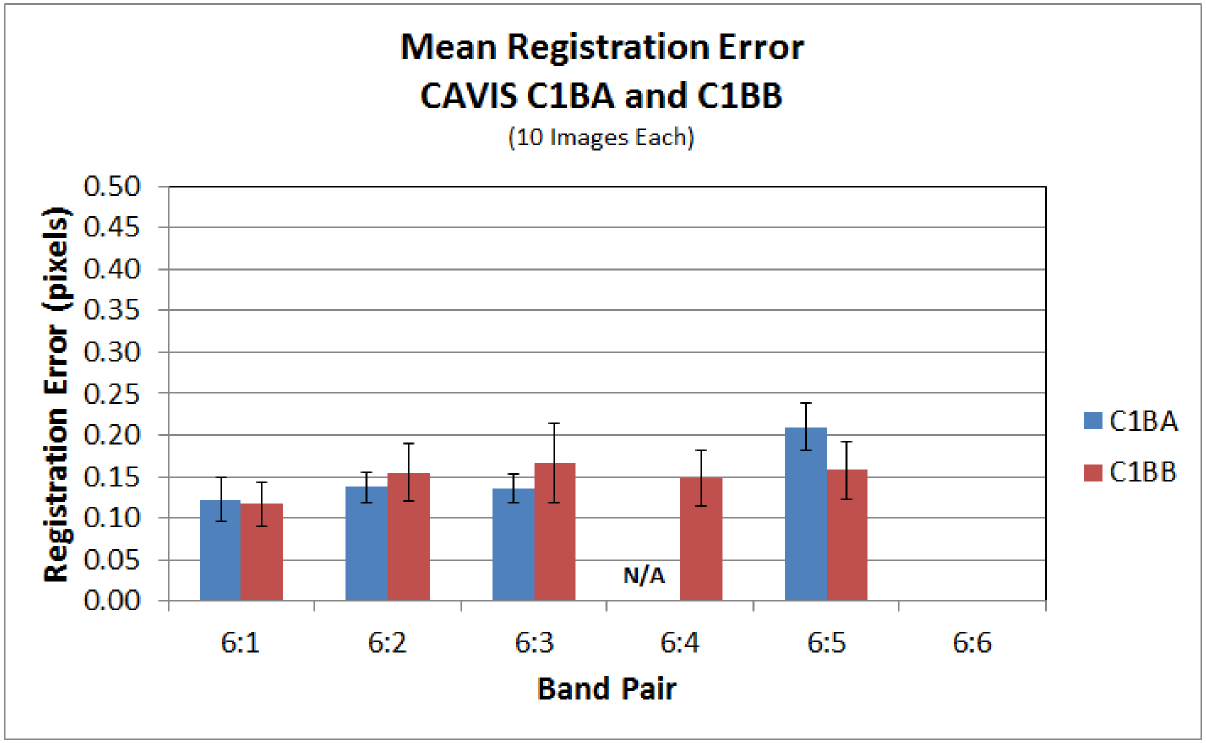
WorldView-3 CAVIS Basic 1B Band Co-Registration Results

C1BA

#	IID	
1	1	15AUG05175644-C1BA-500461846010_01_P001
2	5	15MAR20085012-C1BA-500461846050_01_P001
3	6	15MAR04025355-C1BA-500461846060_01_P001
4	7	15FEB28175414-C1BA-500461846070_01_P001
5	8	15FEB15161141-C1BA-500461846080_01_P001
6	9	15FEB15161400-C1BA-500461846090_01_P001
7	10	15FEB15174827-C1BA-500461846100_01_P001
8	11	15FEB03210325-C1BA-500461846110_01_P001
9	12	15FEB03210228-C1BA-500461846120_01_P001
10	13	15JAN23150254-C1BA-500461846130_01_P001

C1BB

#	IID	
1	1	15AUG05175646-C1BB-500461846010_01_P001
2	5	15MAR20085010-C1BB-500461846050_01_P001
3	6	15MAR04025357-C1BB-500461846060_01_P001
4	7	15FEB28175416-C1BB-500461846070_01_P001
5	8	15FEB15161143-C1BB-500461846080_01_P001
6	9	15FEB15161358-C1BB-500461846090_01_P001
7	10	15FEB15174829-C1BB-500461846100_01_P001
8	11	15FEB03210322-C1BB-500461846110_01_P001
9	12	15FEB03210230-C1BB-500461846120_01_P001
10	13	15JAN23150256-C1BB-500461846130_01_P001



Registration accuracy excellent

No difference between C1BA and C1BB at the 95% confidence level

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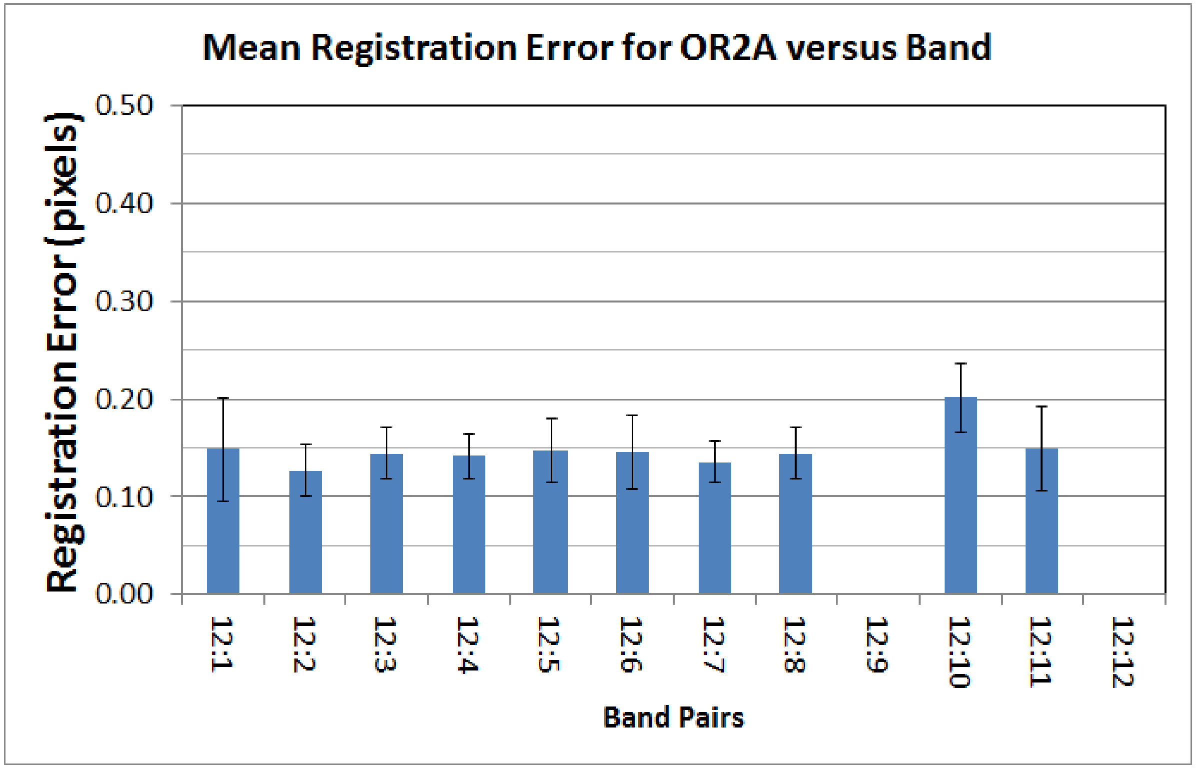
WorldView-3 CAVIS OR2A Band Co-Registration Results

OR2A

#	IID	
1	1	15AUG05175648-C2AS-500461524010_01_P001
2	5	15MAR20084954-C2AS-500461524050_01_P001
3	6	15MAR04025359-C2AS-500461524060_01_P001
4	7	15FEB28175417-C2AS-500461524070_01_P001
5	8	15FEB15161145-C2AS-500461524080_01_P001
6	9	15FEB15161357-C2AS-500461524090_01_P001
7	10	15FEB15174830-C2AS-500461524100_01_P001
8	11	15FEB03210321-C2AS-500461524110_01_P001
9	12	15FEB03210231-C2AS-500461524120_01_P001
10	13	15JAN23150259-C2AS-500461524130_01_P001

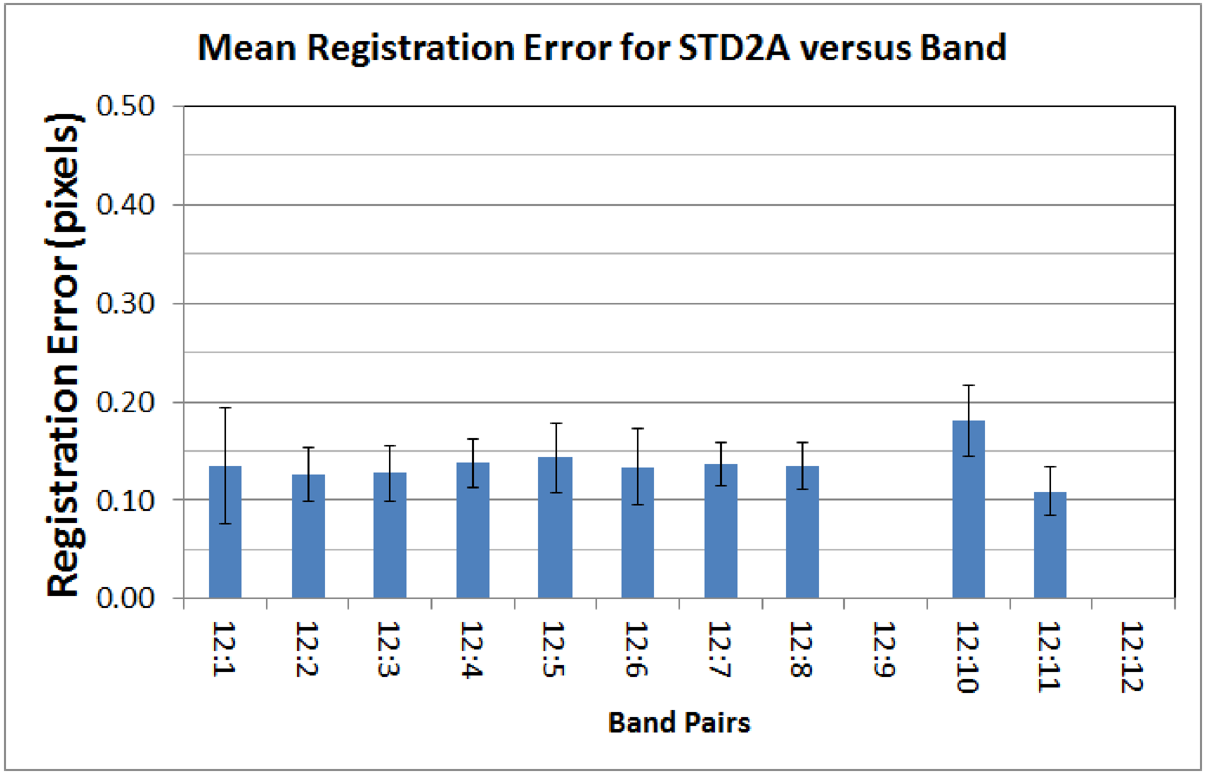


Registration accuracy excellent

WorldView-3 CAVIS Std 2A Band Co-Registration Results

STD2A

#	IID	
1	1	15AUG05175648-C2AS-500453702010_01_P001
2	5	15MAR20084954-C2AS-500453702050_01_P001
3	6	15MAR04025359-C2AS-500453702060_01_P001
4	7	15FEB28175417-C2AS-500453702070_01_P001
5	9	15FEB15161357-C2AS-500453702090_01_P001
6	10	15FEB15174830-C2AS-500453702100_01_P001
7	11	15FEB03210321-C2AS-500453702110_01_P001
8	12	15FEB03210231-C2AS-500453702120_01_P001
9	13	15JAN23150259-C2AS-500453702130_01_P001
10	14	15JAN20155718-C2AS-500453702140_01_P001



Registration accuracy excellent

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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

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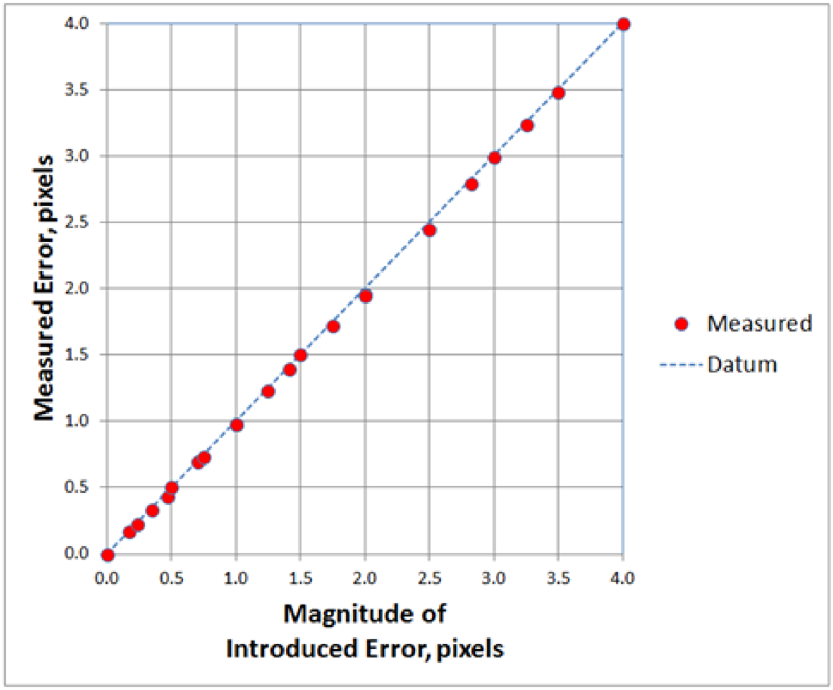
Backups

Co-Registration Measurement Validation



Introduced Error pixels	Measured* Mean Error pixels	Std Deviation pixels
0.000	0.000	0.000
0.177	0.165	0.017
0.236	0.219	0.012
0.354	0.332	0.011
0.471	0.428	0.008
0.500	0.503	0.032
0.707	0.696	0.041
0.750	0.735	0.012
1.000	0.978	0.005
1.000	0.978	0.005
1.000	0.975	0.009
1.250	1.229	0.038
1.414	1.392	0.005
1.500	1.502	0.020
1.750	1.718	0.021
2.000	1.961	0.010
2.000	1.958	0.019
2.000	1.949	0.009
2.500	2.443	0.060
2.828	2.790	0.015
3.000	2.993	0.003
3.250	3.233	0.013
3.500	3.480	0.034
4.000	3.998	0.002

*Each measurement based on four samples

Mean Difference Between the Introduced and Measured Error

= 0.022 ± 0.0051; 90% Conf.

Purposely introduced errors into a copy of the same image

Measured the registration errors between the original and copy

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