NATIONAL GEOSPATIAL-INTELLIGENCE AGENCY

Know the Earth... Show the Way... Understand the World

WorldView-3 Absolute Geolocation Accuracy Evaluation

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Joint Agency Commercial Imagery Evaluation Workshop
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Outline

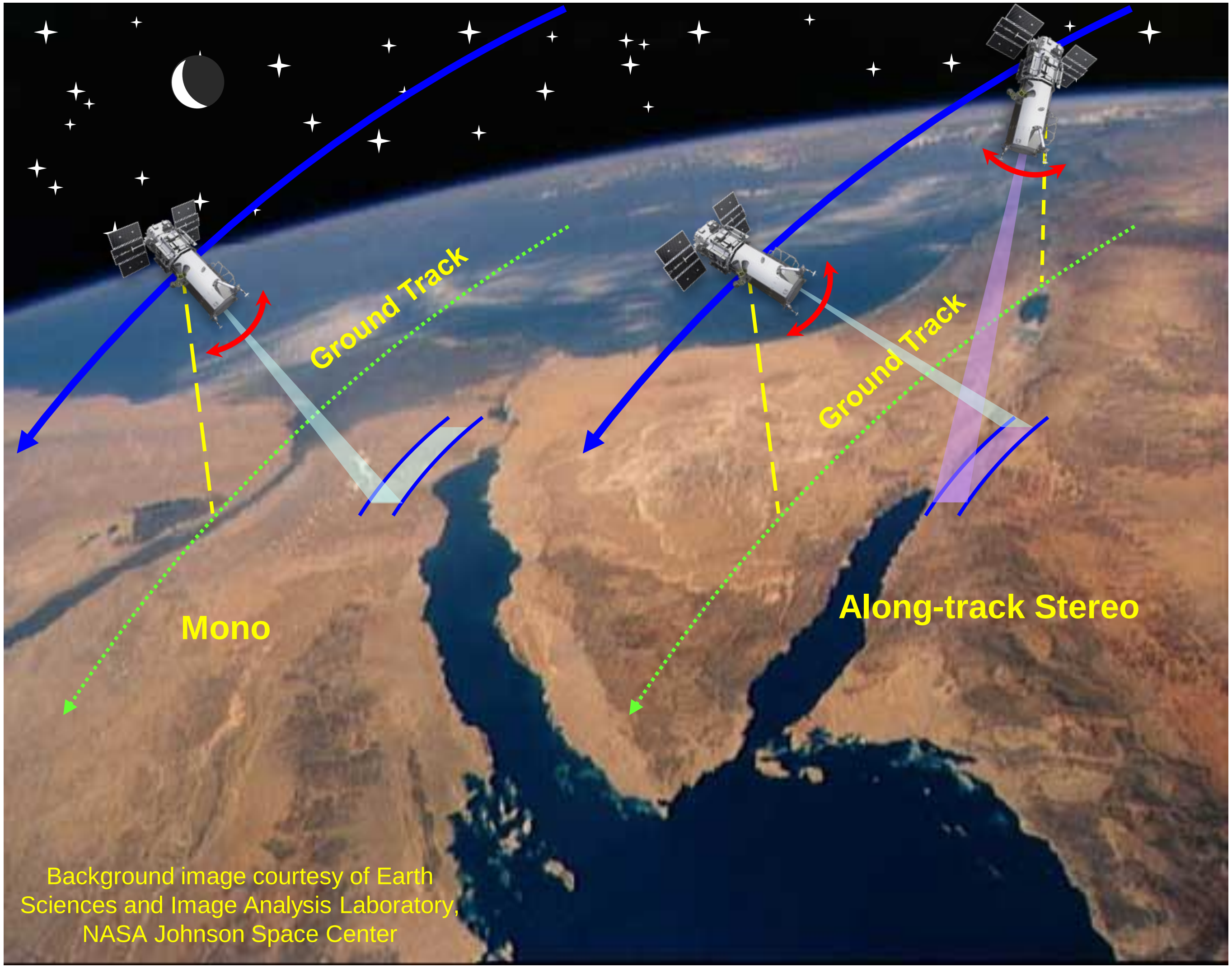
- Background
- Evaluation
- Results

WorldView-3

© DigitalGlobe
https://www.digitalglobe.com/sites/default/files/styles/satellite/public/WorldView-3.png

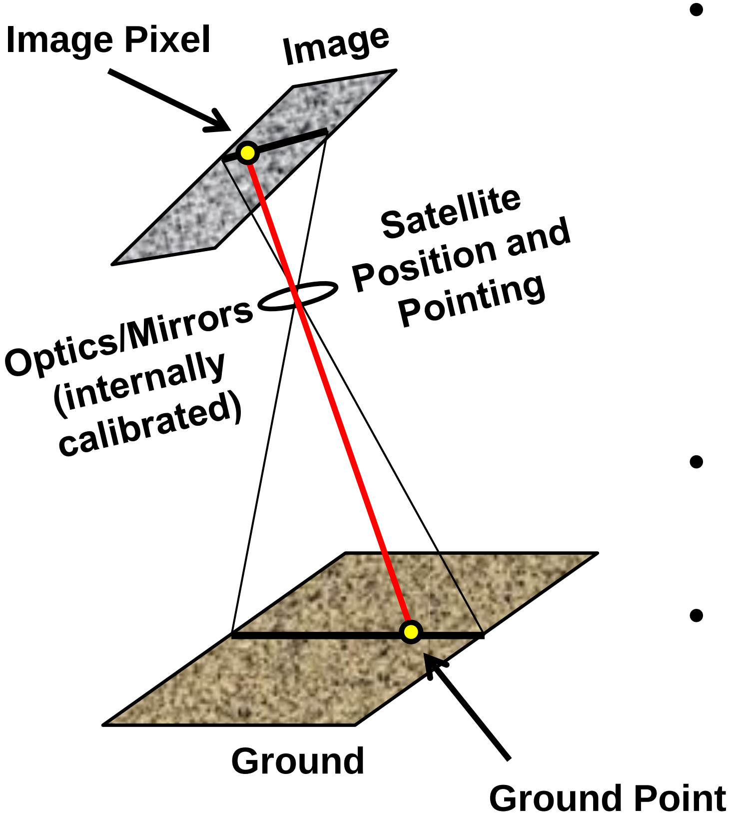
- Owned by DigitalGlobe (DG)
- Launched: 13 August 2014
- Direct geo-location
  - GPS receiver on-board used to determine orbital position
  - Inertial Reference Units and Star Trackers used to determine pointing direction
  - Sensor and its relationship to GPS and star trackers are highly calibrated

Mono and Stereo Collection



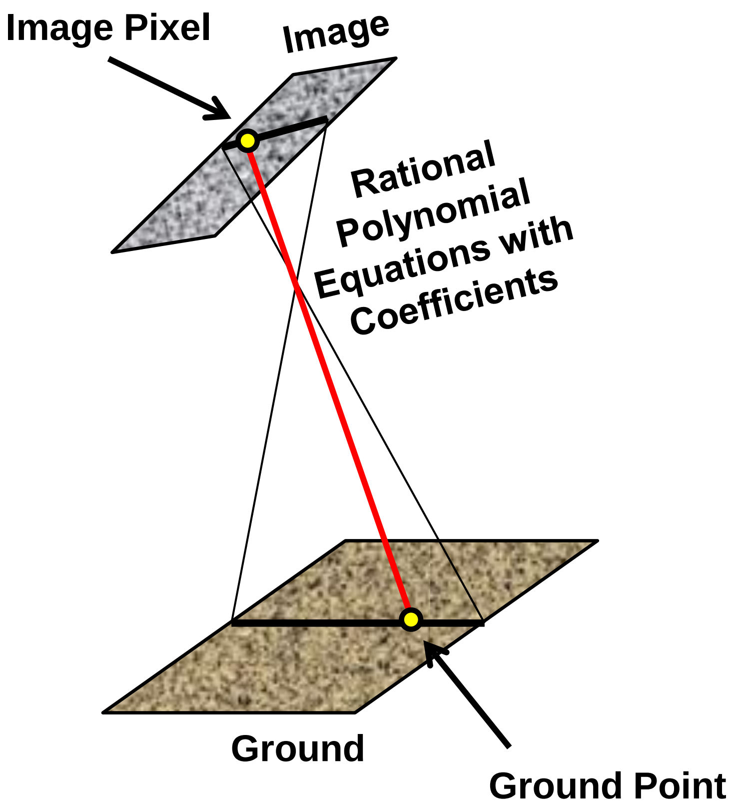
- Agile scanning
  - Forward
  - Reverse
- Along-track stereo
- Off-nadir angles typically < 30°

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



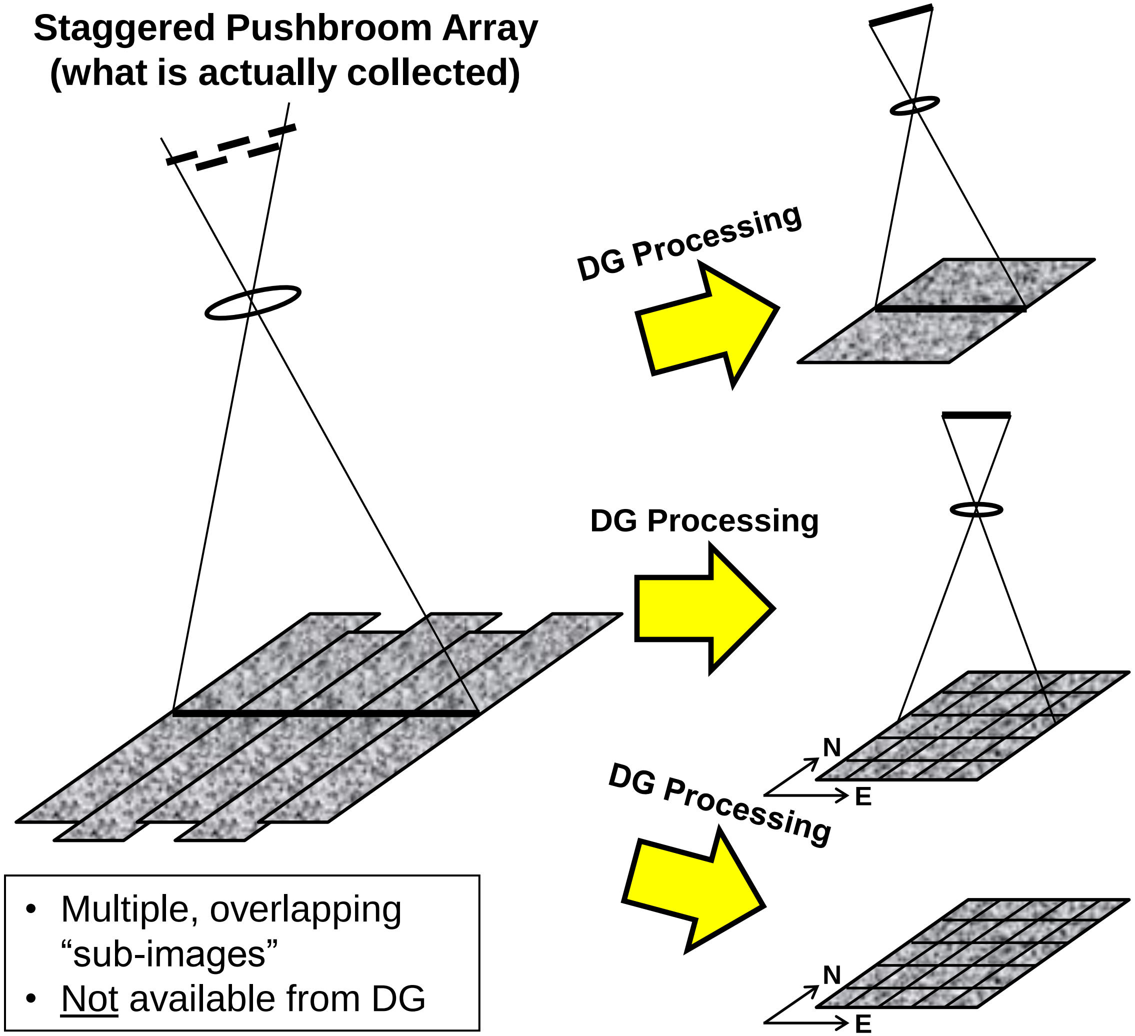
- Relates image pixels to ground positions, but using ratio of 3rd order polynomial equations

  image line = f_1(lat,long,height)

  image sample = 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

Geometry of Product Processing

Staggered Pushbroom Array
(what is actually collected)



- Multiple, overlapping "sub-images"
- <u>Not</u> available from DG

Only these two processing levels evaluated.

<u>Basic 1B Product</u>
- Synthetic Pushbroom Array
- Image <u>not</u> on map grid (i.e., "raw')
- Sensor model data available for geolocation:
  1) Pushbroom physical model
  2) RPC replacement model

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

<u>Orthorectified Image</u>
- To terrain (or surface) model
- On map grid, <u>although</u> objects not in model are <u>not</u> 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

- 1st 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)
- 2nd 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

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

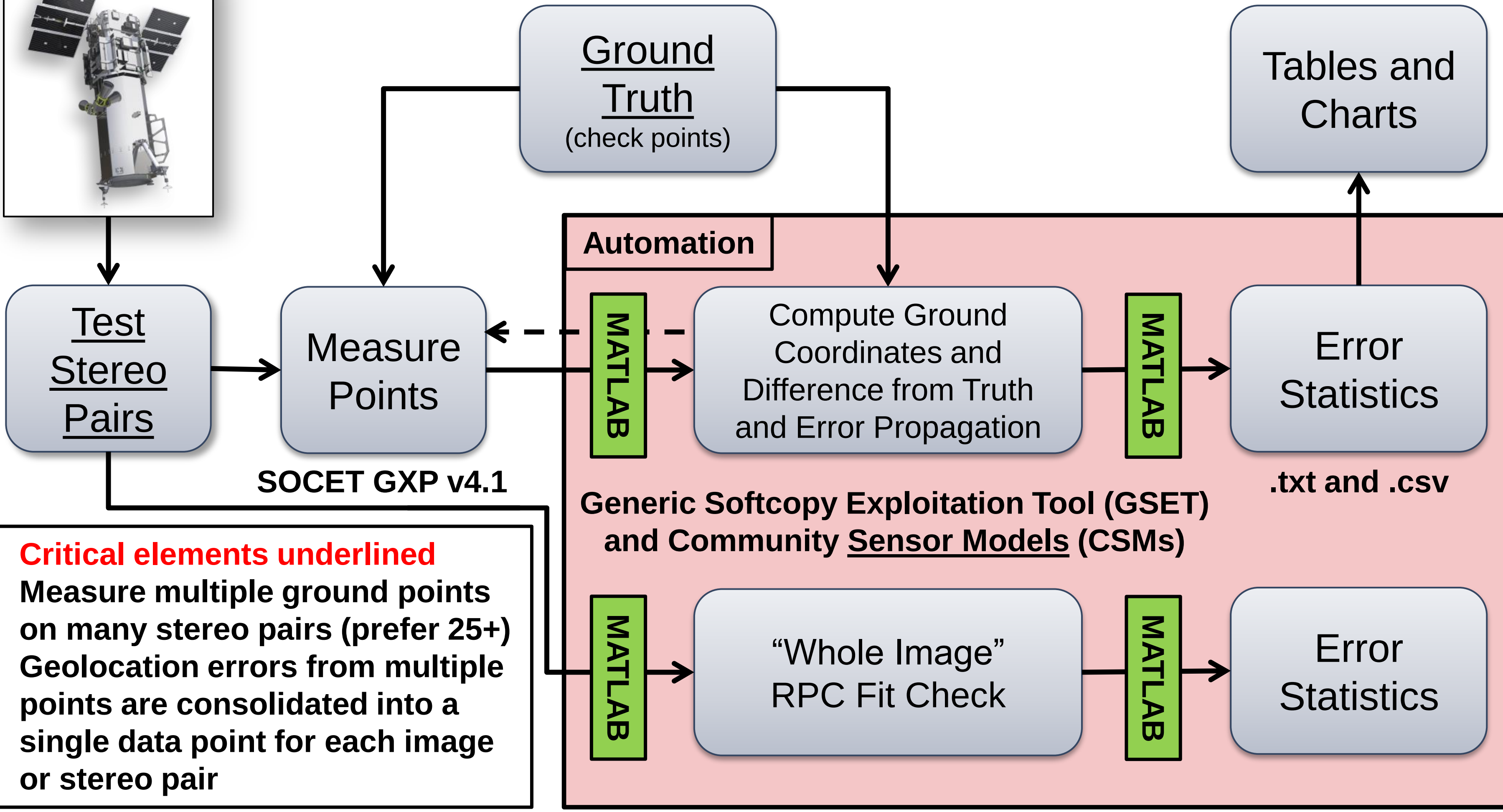
Ground Truth

- 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)



- **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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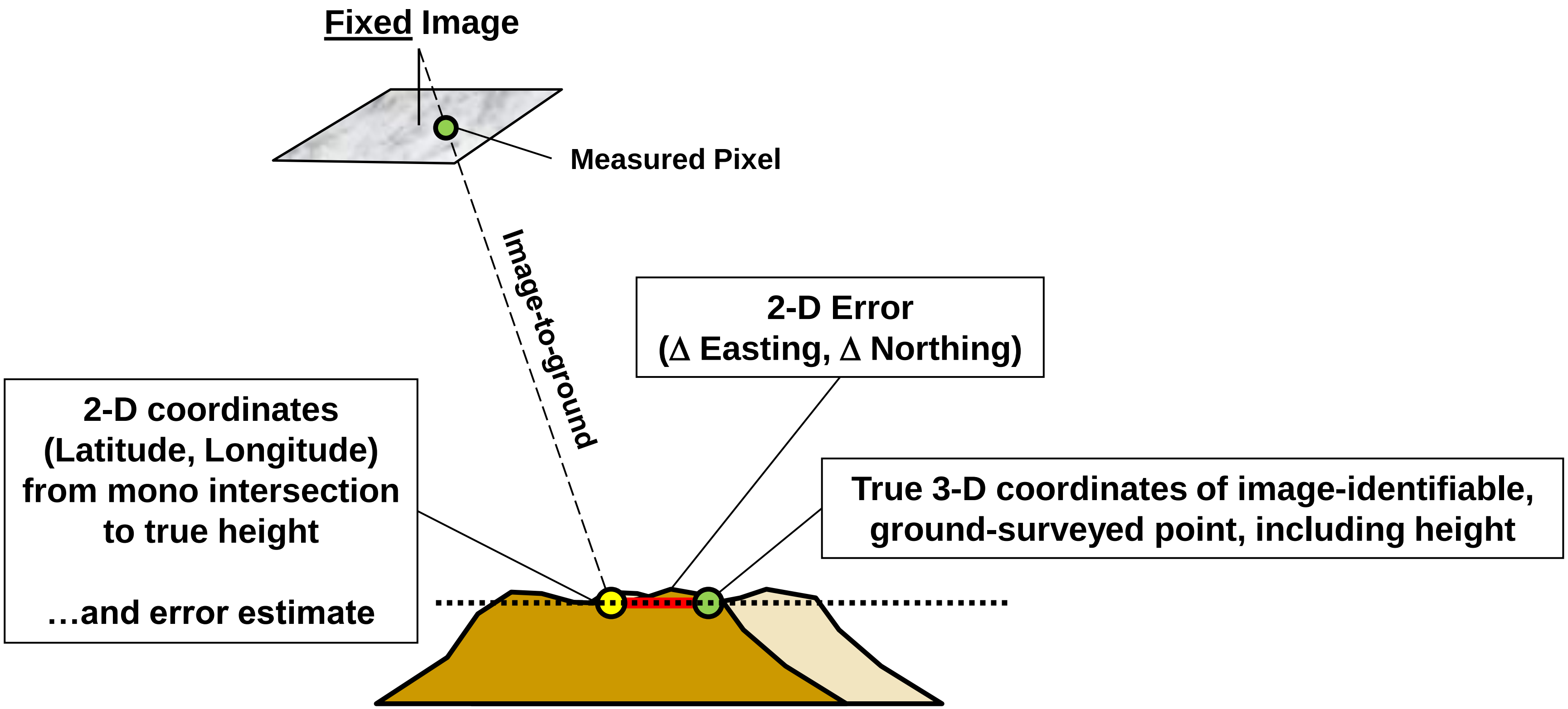
Mono Intersection



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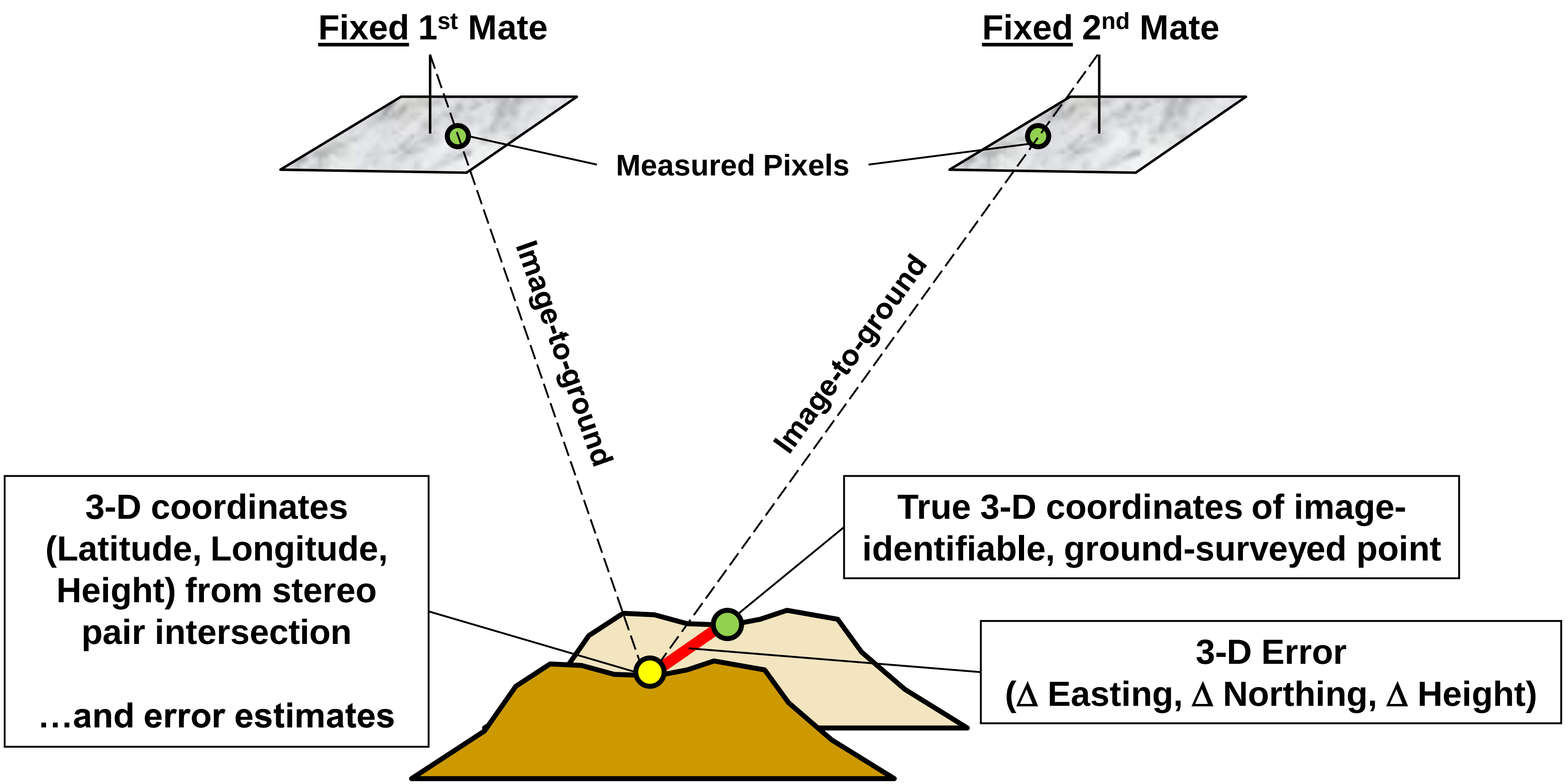
Stereo Intersection



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*33+0.5 = 30.2 → linearly interpolate between $X_{(30)}$ and $X_{(31)}$ values

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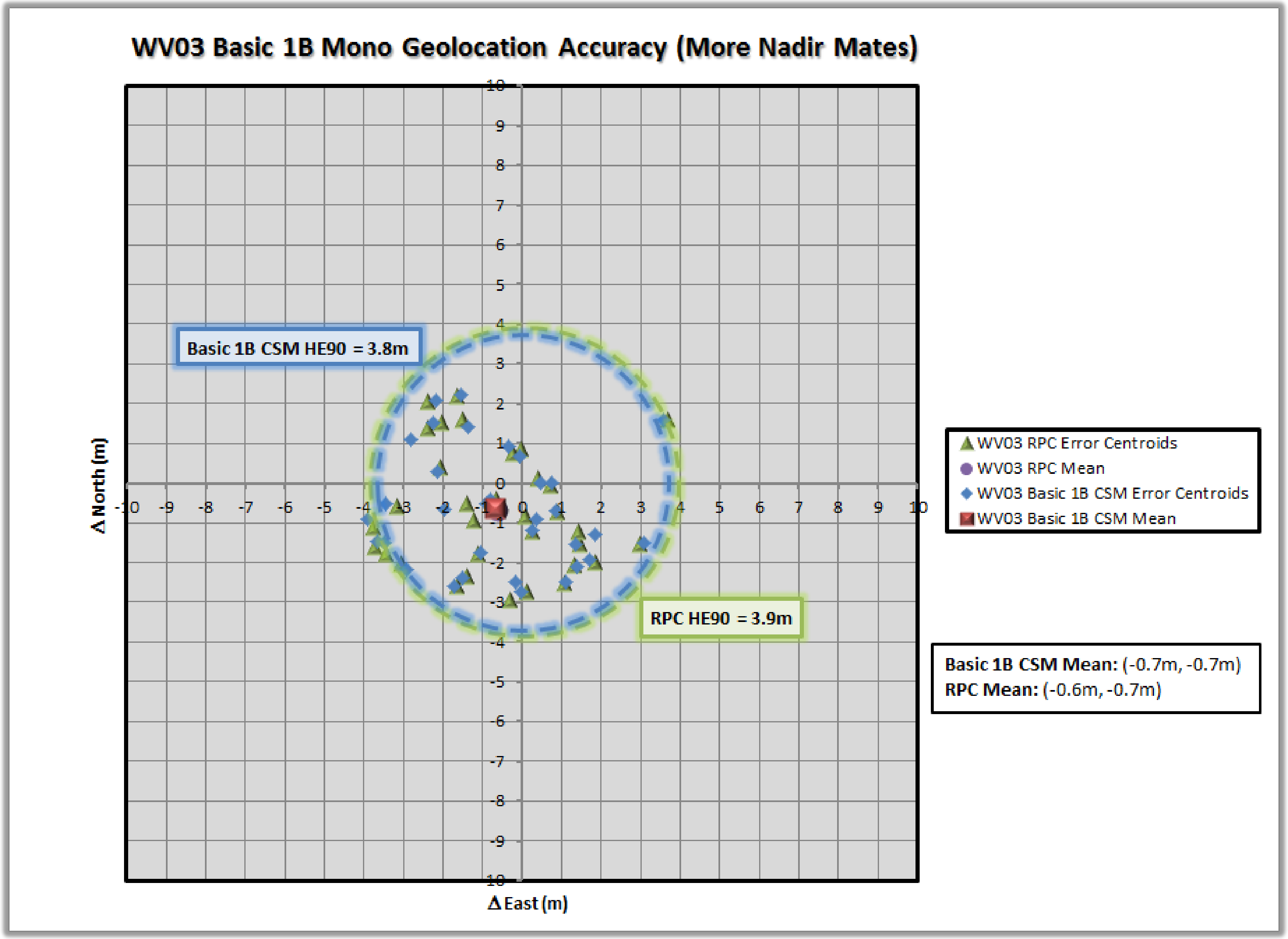
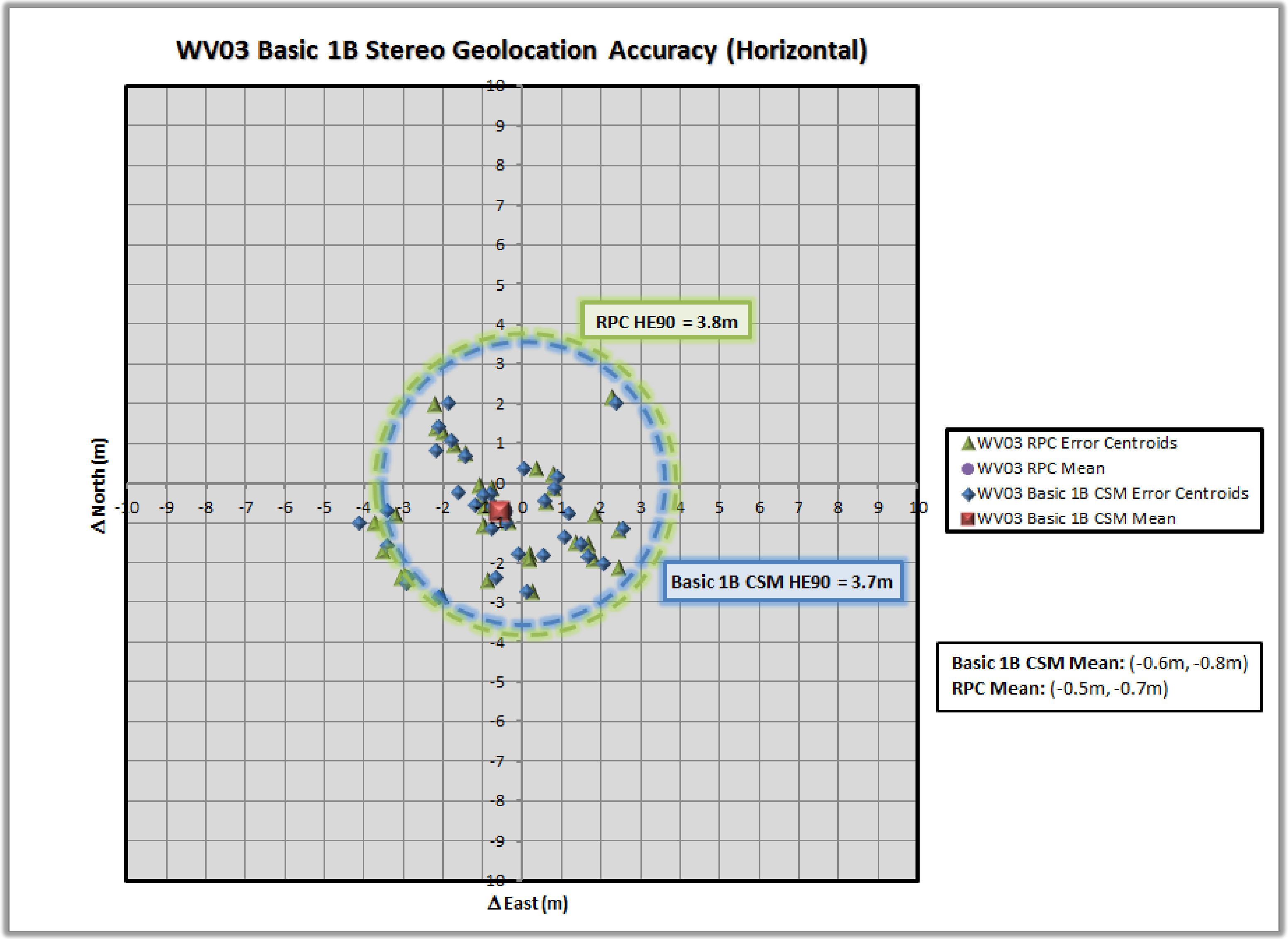
WV03 Absolute Geolocation Accuracy Results

Sample size of 33 WorldView-3 Basic 1B Stereo Pairs (Physical Model)		
	Estimated Value	Confidence Statements
Sample Mono HE90	3.8 m	> 96% confidence that True CE90 < 4.1m
Sample Stereo HE90	3.7 m	> 96% confidence that True CE90 < 4.3m
Sample Stereo VE90	2.7 m	> 96% confidence that True LE90 < 5.0m

Sample size of 33 WorldView-3 Basic 1B Stereo Pairs (RPC)		
	Estimated Value	Confidence Statements
Sample Mono HE90	3.9 m	> 96% confidence that True CE90 < 4.1m
Sample Stereo HE90	3.8 m	> 96% confidence that True CE90 < 3.9m
Sample Stereo VE90	2.7 m	> 96% confidence that True LE90 < 6.3m

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


WV03 Basic 1B Mono Geolocation Accuracy (More Nadir Mates)
Basic 1B CSM HE90 = 3.8m
RPC HE90 = 3.9m
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: (-0.7m, -0.7m)
RPC Mean: (-0.6m, -0.7m)



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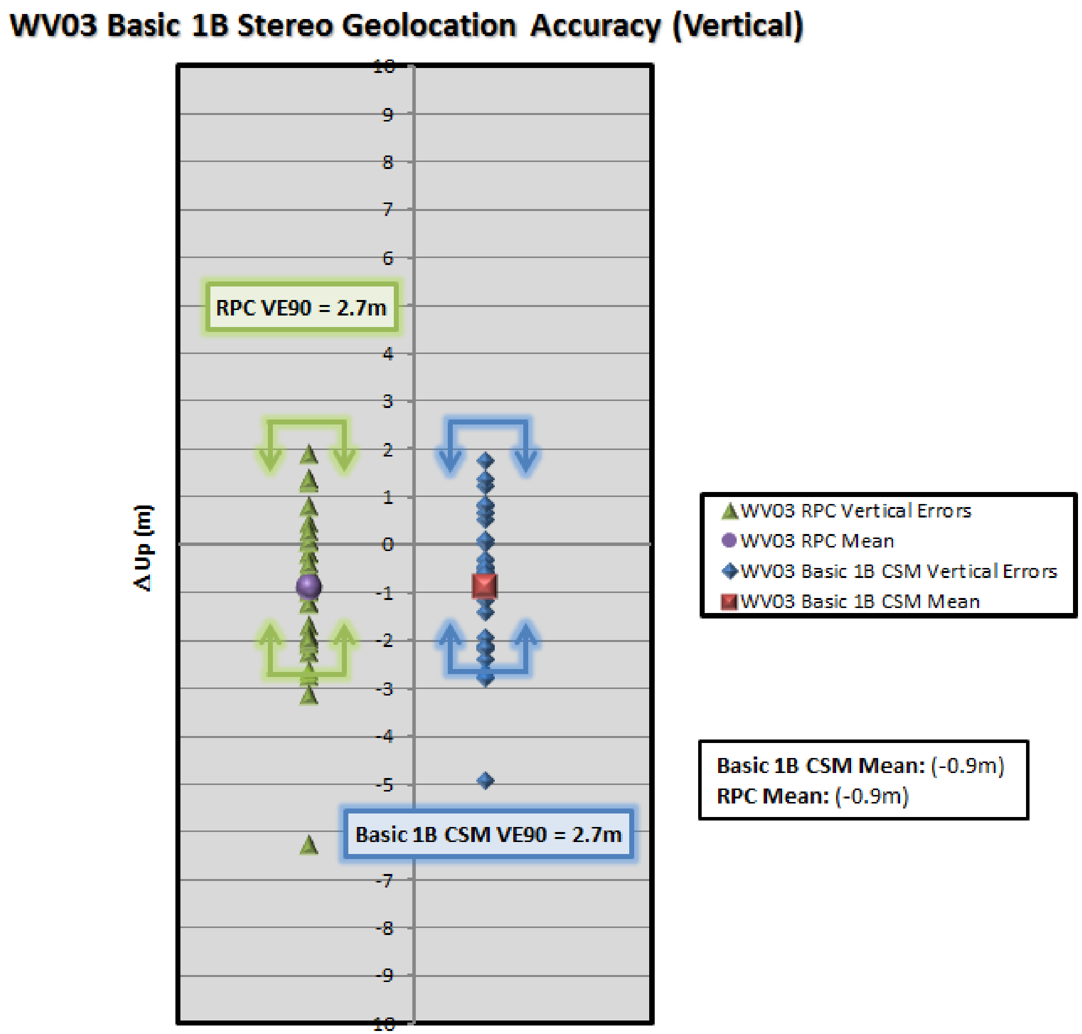
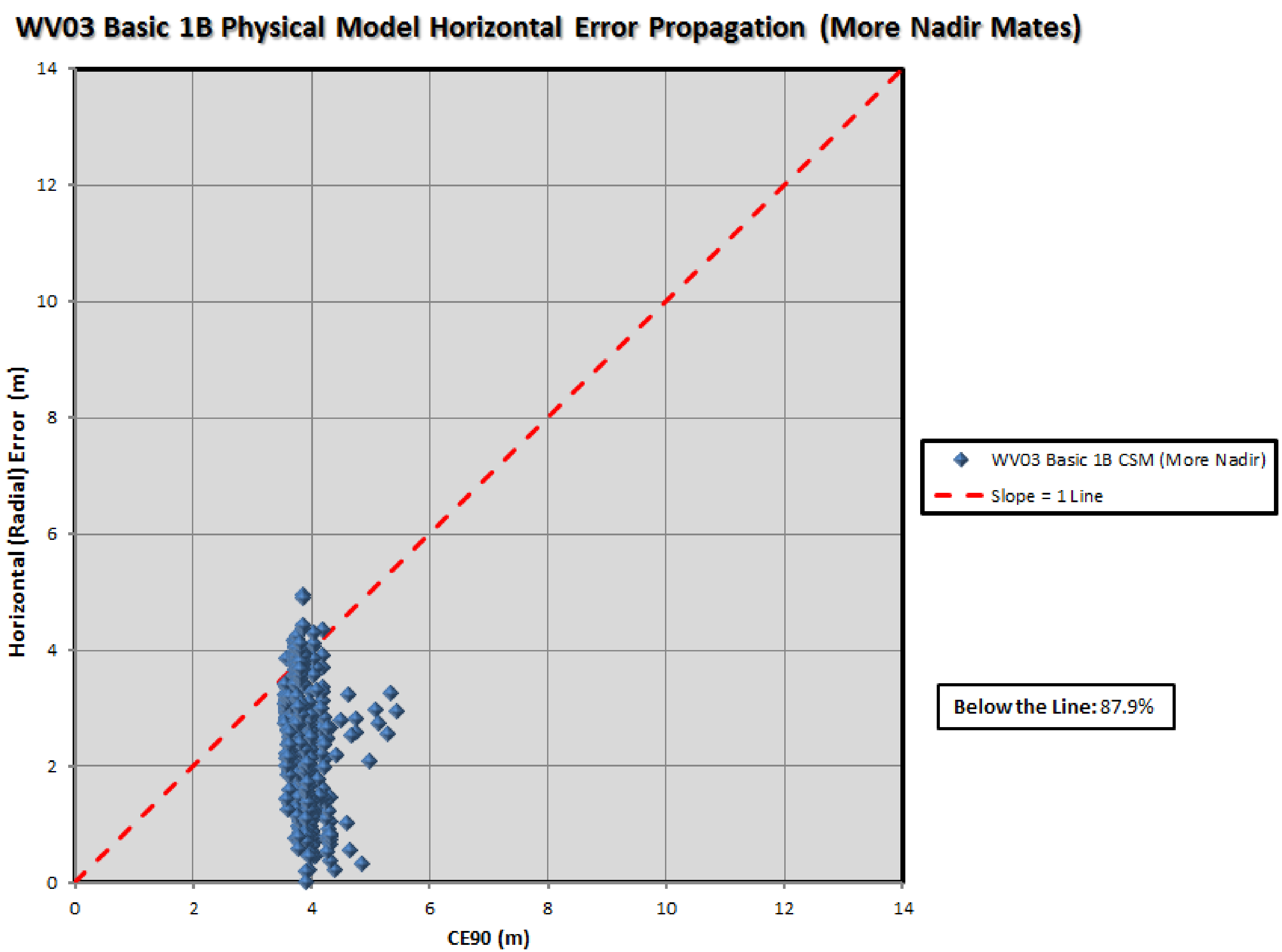


Basic 1B CSM Mean: (-0.9m)
RPC Mean: (-0.9m)

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



Below the Line: 87.9%

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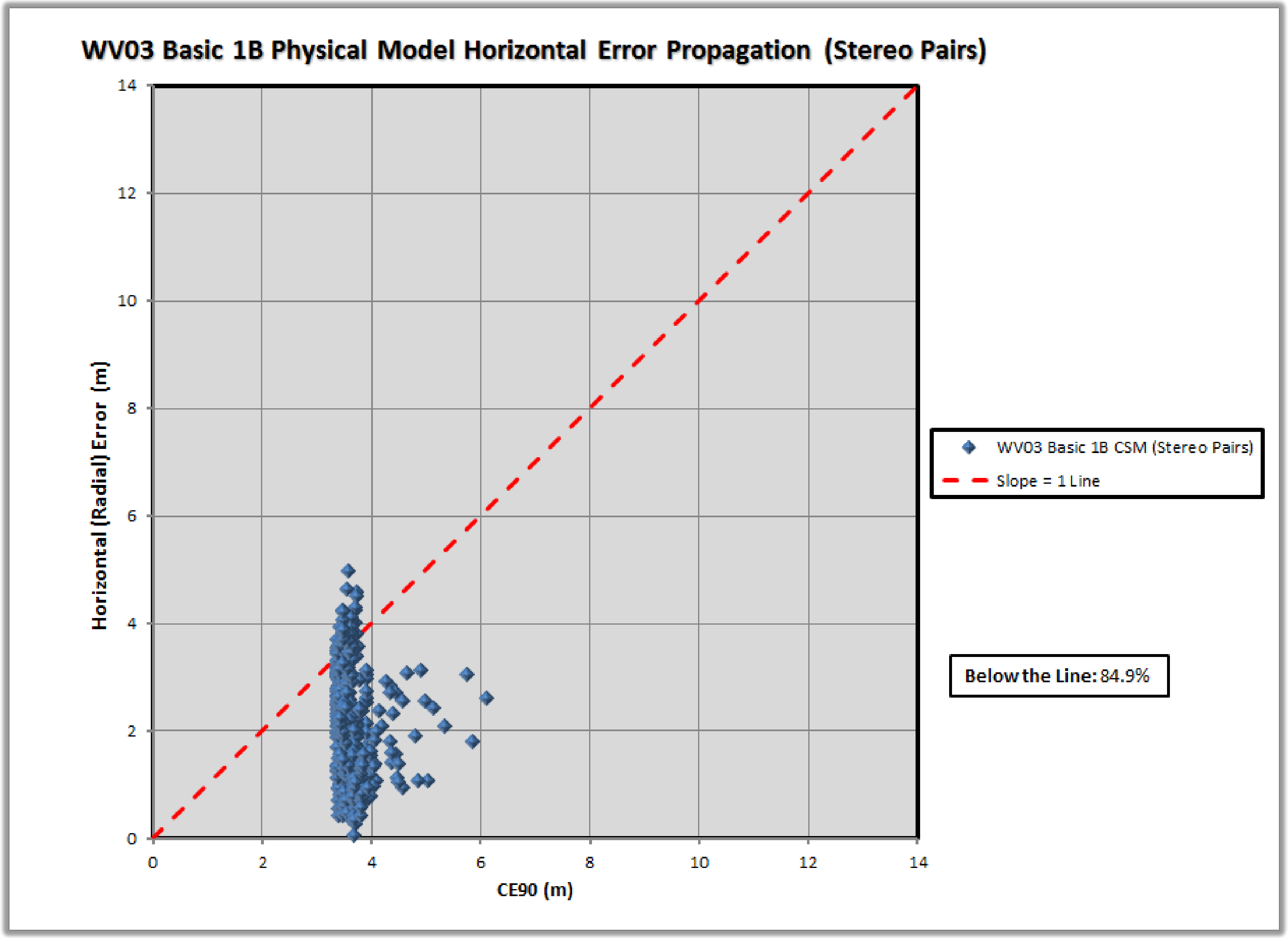

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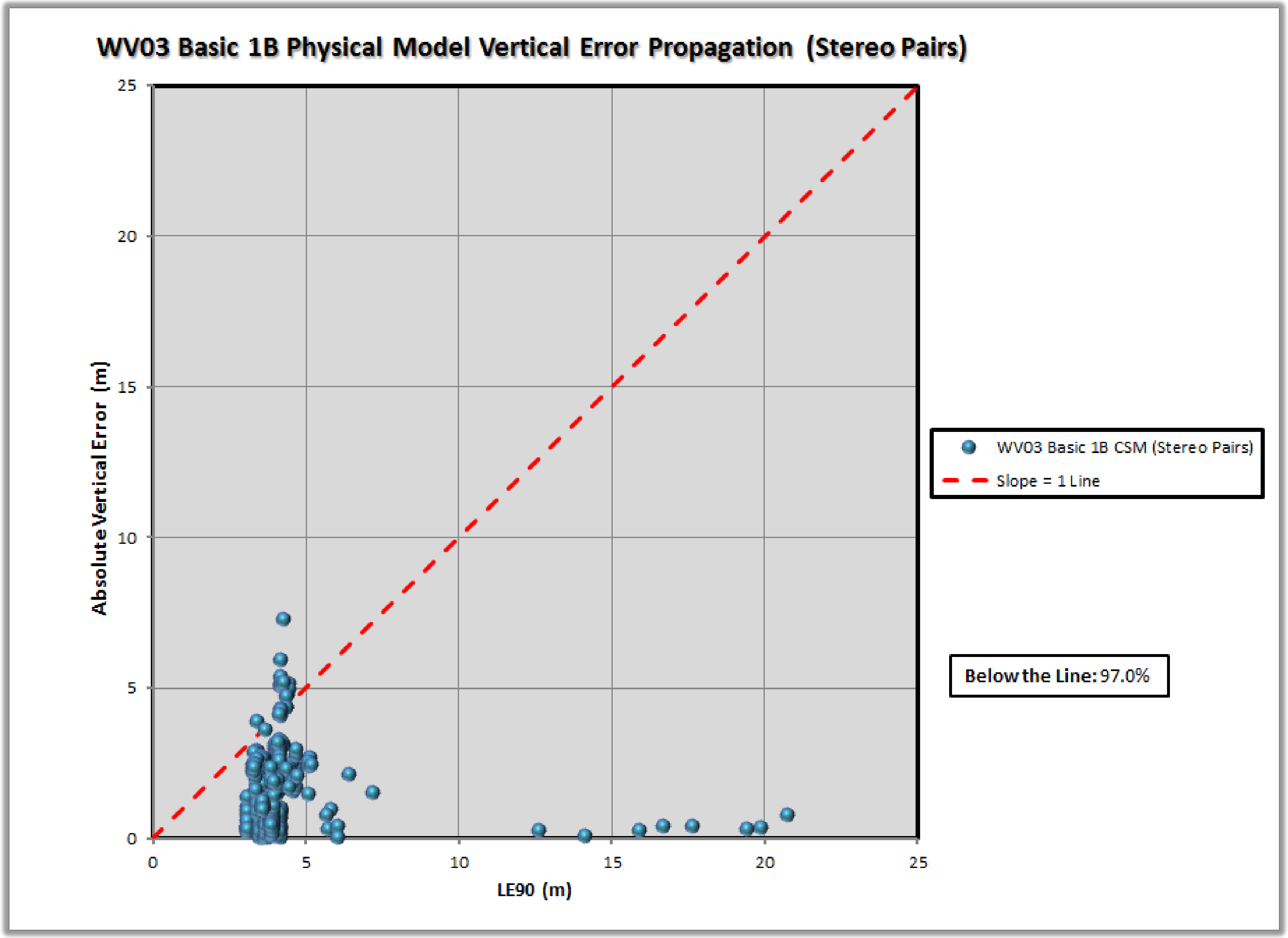

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WV03 Error Propagation Summary

Error Propagation (% Below Slope = 1 Line)		
All 507 Points	Physical Model	RPC
More Nadir Mono Horizontal	85.2%	64.1%
More Off-Nadir Mono Horizontal	91.3%	72.0%
Stereo Horizontal	80.9%	64.3%
Stereo Vertical	96.7%	84.4%

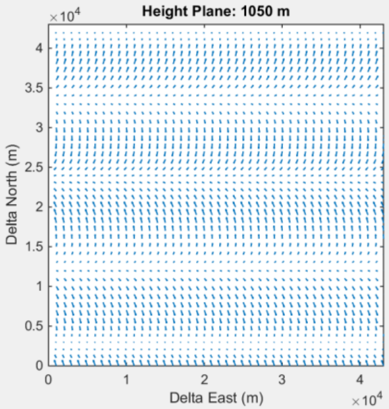
Error Propagation (% Below Slope = 1 Line)		
Based on Ave for 33 Images	Physical Model	RPC
More Nadir Mono Horizontal	87.9%	69.7%
More Off-Nadir Mono Horizontal	87.9%	78.8%
Stereo Horizontal	84.9%	72.7%
Stereo Vertical	97.0%	90.9%

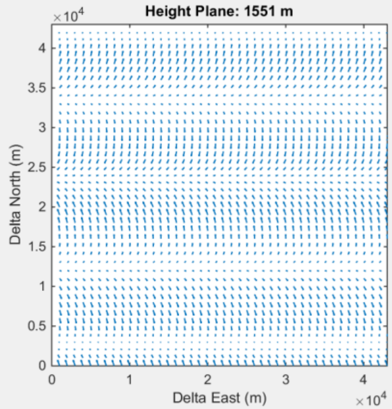
- Ideally values should be 90%

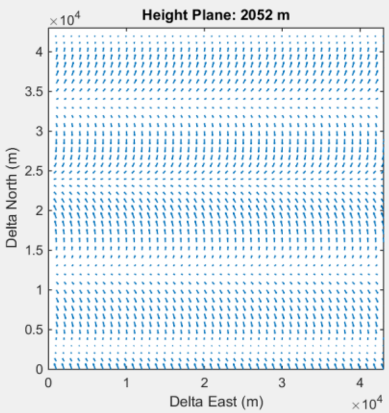
"Whole Image" RPC Fit Analysis

- 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







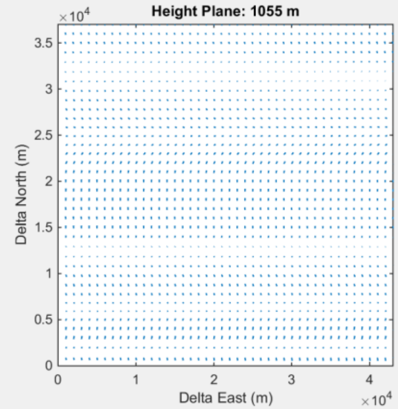
KE-Jomo-Kenyatta-Kenya
14DEC20080217-P1BS-500233720010-01-P001

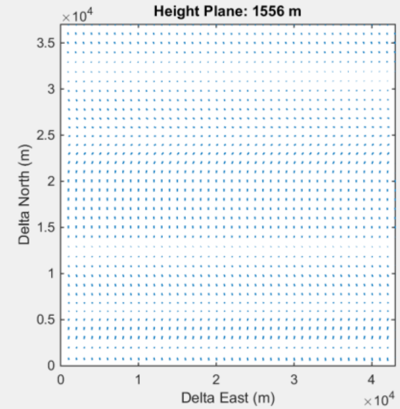
Height Plane: 1050 m
mean:(0.0m, 0.0m)
max:(0.3m, 0.7m)
min:(-0.3m, -0.7m)
max mag: 0.8m

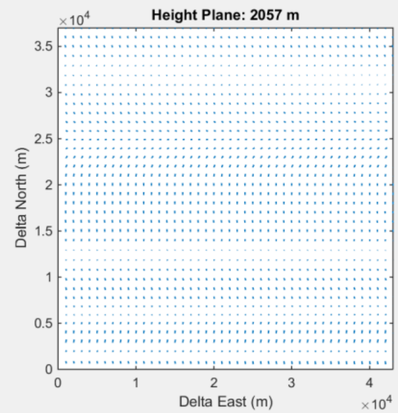
Height Plane: 1551 m
mean:(0.0m, 0.0m)
max:(0.3m, 0.7m)
min:(-0.3m, -0.7m)
max mag: 0.8m

Height Plane: 2052 m
mean:(0.0m, 0.0m)
max:(0.3m, 0.7m)
min:(-0.3m, -0.7m)
max mag: 0.8m

More Nadir







KE-Jomo-Kenyatta-Kenya
14DEC20080306-P1BS-500233720020-01-P001

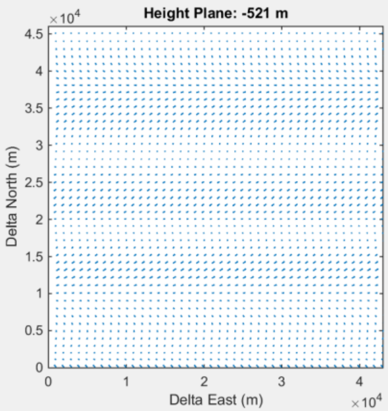
Height Plane: 1055 m
mean:(0.1m, 0.1m)
max:(0.2m, 0.4m)
min:(-0.1m, -0.3m)
max mag: 0.4m

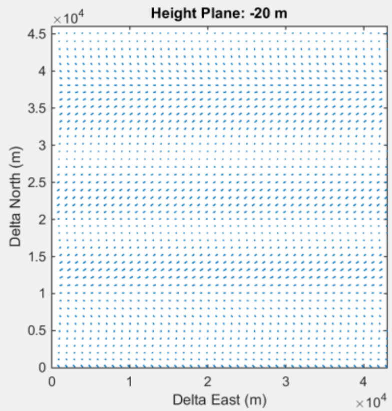
Height Plane: 1556 m
mean:(0.1m, 0.1m)
max:(0.2m, 0.4m)
min:(-0.1m, -0.3m)
max mag: 0.4m

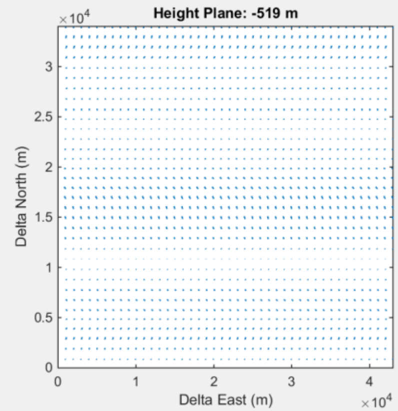
Height Plane: 2057 m
mean:(0.1m, 0.1m)
max:(0.2m, 0.4m)
min:(-0.1m, -0.3m)
max mag: 0.4m

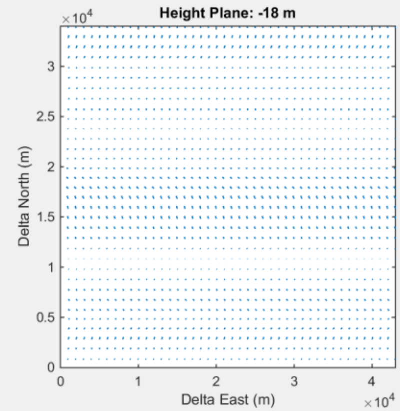
More Off-Nadir

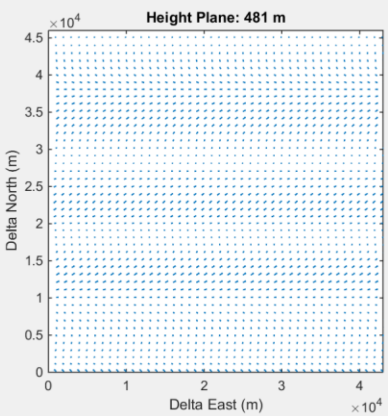
Masirah Island, Oman









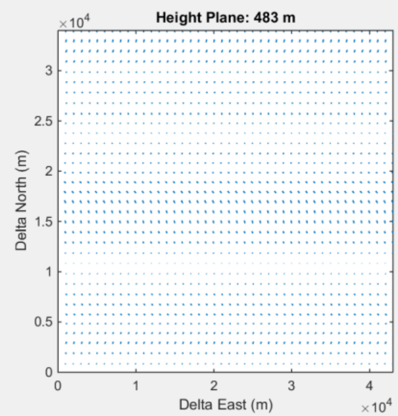


OM-Masirah-Island-Oman
14DEC21063506-P1BS-500233724010-01-P001

Height Plane: -521 m
mean:(0.1m, 0.0m)
max:(0.4m, 0.3m)
min:(-0.3m, -0.3m)
max mag: 0.5m

Height Plane: -20 m
mean:(0.0m, 0.0m)
max:(0.4m, 0.3m)
min:(-0.3m, -0.3m)
max mag: 0.5m

Height Plane: 481 m
mean:(0.0m, 0.0m)
max:(0.4m, 0.3m)
min:(-0.3m, -0.3m)
max mag: 0.5m



OM-Masirah-Island-Oman
14DEC21063555-P1BS-500233724020-01-P001

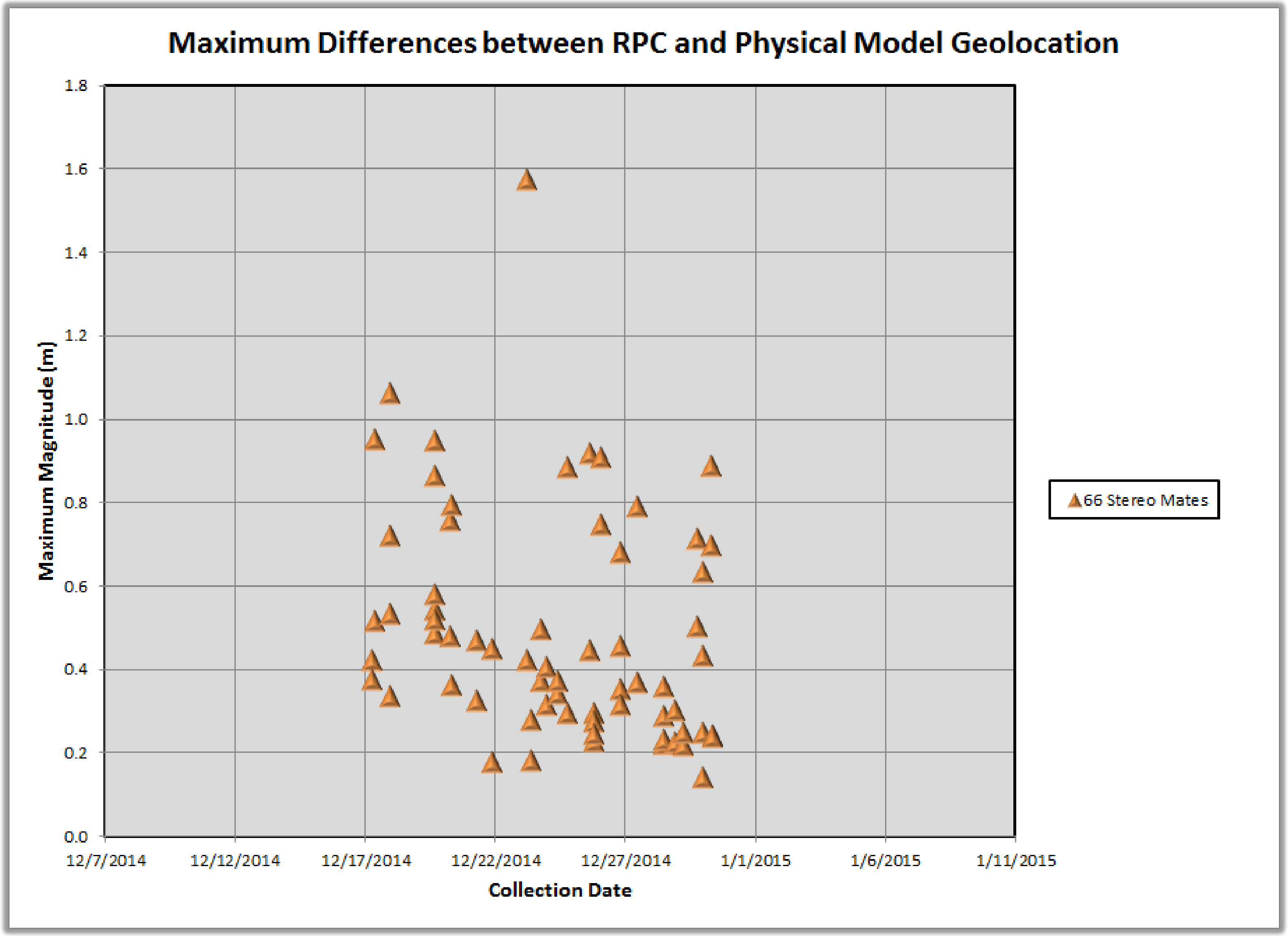
Height Plane: -519 m
mean:(0.0m, 0.1m)
max:(0.2m, 0.3m)
min:(-0.2m, -0.2m)
max mag: 0.3m

Height Plane: -18 m
mean:(0.0m, 0.1m)
max:(0.2m, 0.3m)
min:(-0.2m, -0.2m)
max mag: 0.3m

Height Plane: 483 m
mean:(0.0m, 0.1m)
max:(0.2m, 0.3m)
min:(-0.2m, -0.2m)
max mag: 0.3m

More Nadir

More Off-Nadir


Maximum Differences between RPC and Physical Model Geolocation
Maximum Magnitude (m)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
12/7/2014
12/12/2014
12/17/2014
12/22/2014
12/27/2014
1/1/2015
1/6/2015
1/11/2015
Collection Date
66 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

Test Site	Basic 1B Product	Ortho-Ready 2A Product	Mono Mates		Stereo Pairs		
			ΔΔ E (m)	ΔΔ N (m)	ΔΔ E (m)	ΔΔ N (m)	ΔΔ U (m)
BO_El_Trompillo_Bolivia	14SEP08141129-P1BS-500167188010_01_P001	14SEP08141127-P2AS-500167237010_01_P001	-0.06	-0.04	0.53	-0.13	0.31
BO_El_Trompillo_Bolivia	14SEP08141217-P1BS-500167188020_01_P001	14SEP08141215-P2AS-500167237020_01_P001	0.02	-0.01			
OM_Seeb_Oman	14AUG29063533-P1BS-500167159010_01_P001	14AUG29063532-P2AS-500167235010_01_P001	0.02	0.02	0.01	0.03	0.02
OM_Seeb_Oman	14AUG29063633-P1BS-500167159020_01_P001	14AUG29063633-P2AS-500167235020_01_P001	0.02	0.03			
TN_Sidi_Ahmed_Tunisia	14AUG30100117-P1BS-500167158010_01_P001	14AUG30100117-P2AS-500167236010_01_P001	-0.01	0.03	0.48	-0.12	0.03
TN_Sidi_Ahmed_Tunisia	14AUG30100218-P1BS-500167158020_01_P001	14AUG30100218-P2AS-500167236020_01_P001	0.03	0.03			

Summary

- Using 33 Basic 1B stereo pairs (2^{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^{st} dataset
  - OR2A products have comparable geolocation to Basic 1B products

Backups

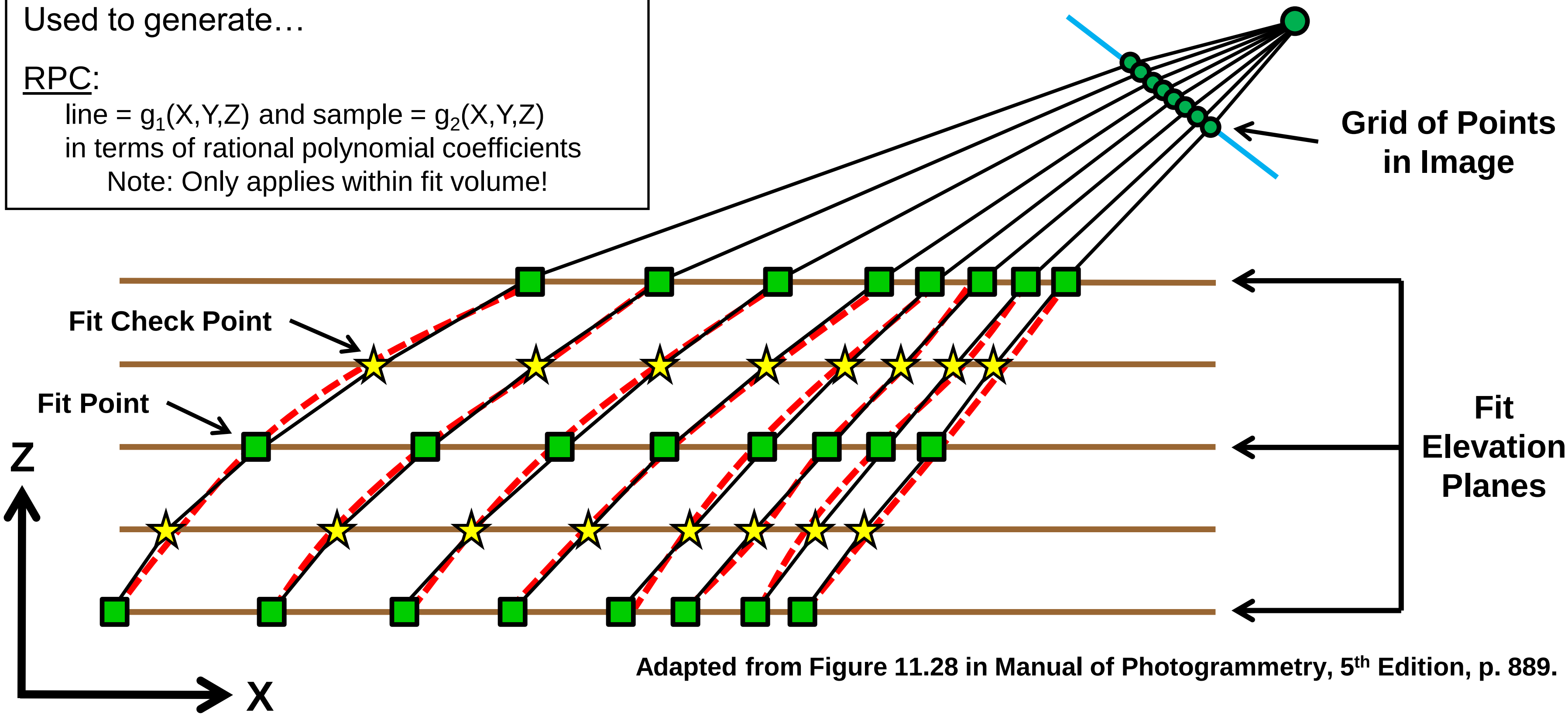
RPC Generation from Physical Model

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



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

Non-Parametric 90th Percentile Estimator for Ordered Statistics

Given n ordered data points $x_{(1)}, x_{(2)}, \ldots, x_{(n)}$, where $x_{(i)} = \Delta r_{(i)}$ for HE90 and $x_{(i)} = abs(\Delta h_{(i)})$ for VE90.

$$\text{HE90 or LE90} = (1 - f)*x_{(i)} + f*x_{(i+1)}$$

with

i = integer part of $0.9*n + 0.5$, and

f = 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) ≤ 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

Reference: Equation 3.2.43 on page 147 of W. J. Conover, *Practical Nonparametric Statistics*, 3rd Edition, John Wiley and Sons, Inc., New York, 1999.

Fictitious Example (Confidence)

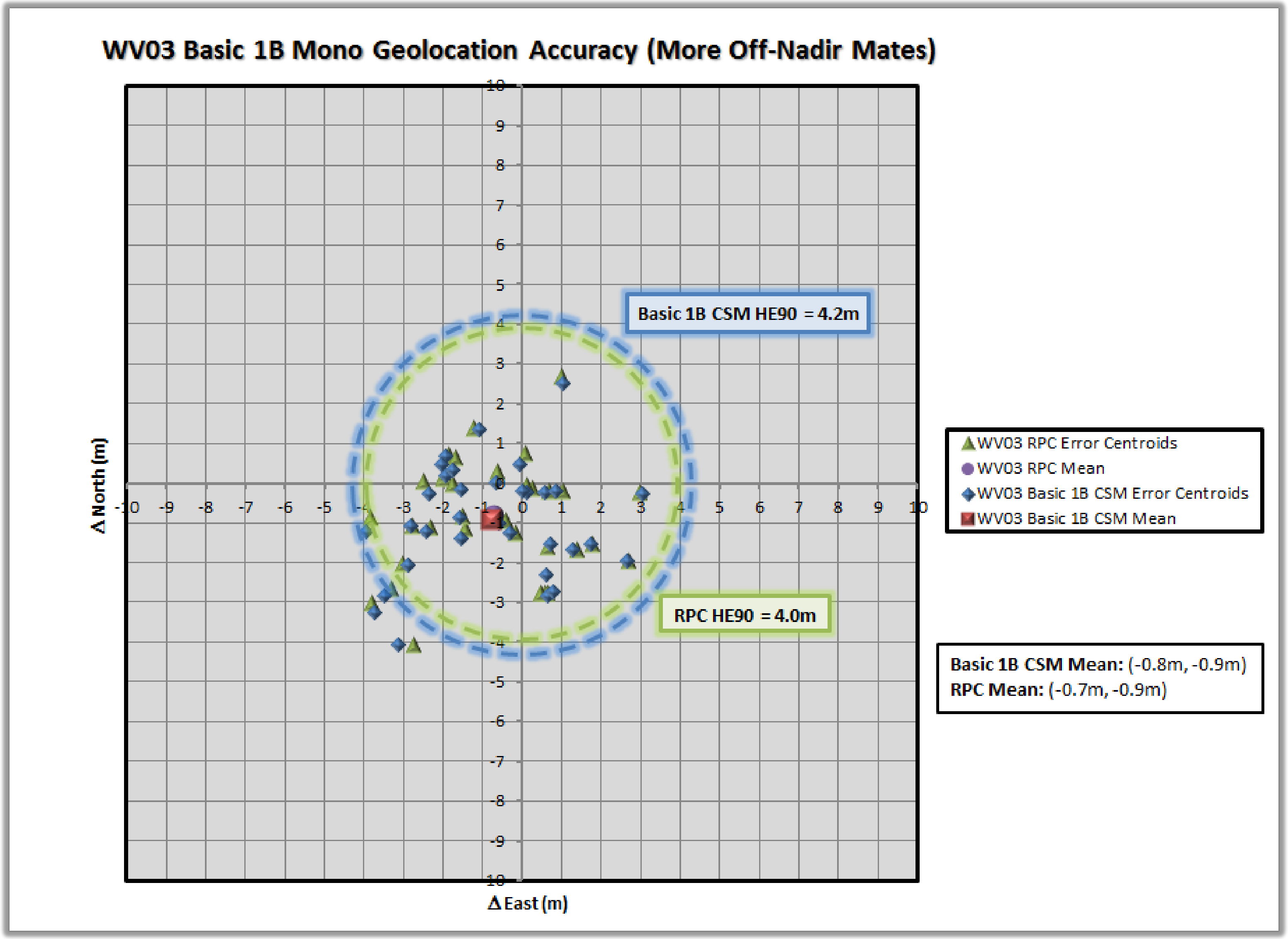
Given an ordered sample set as follows (n=25):

$X_{(1)}$=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%.



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