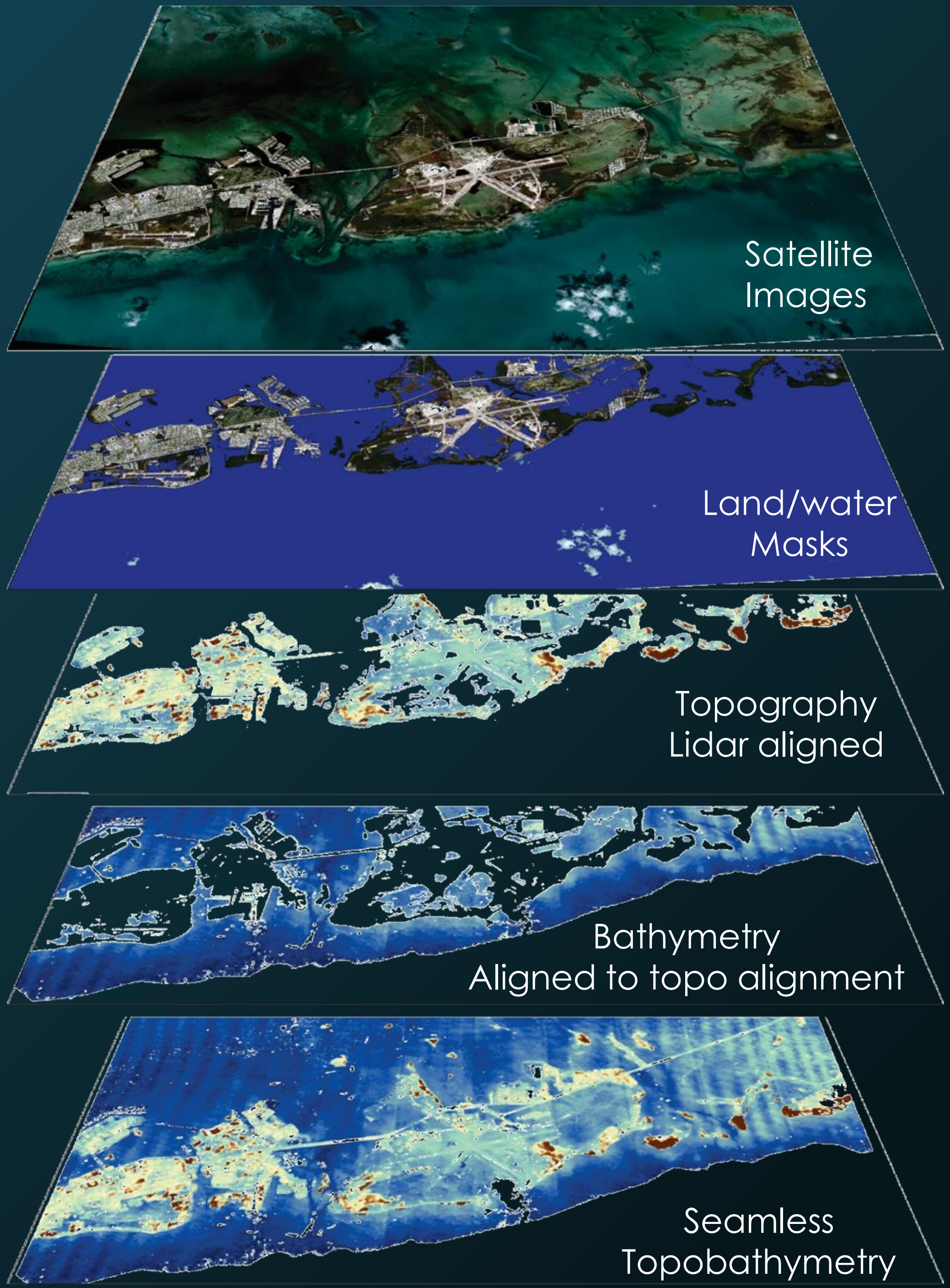
Satellite Triangulated Sea Depth (SaTSeaD) Bathymetry Module for NASA Ames Stereo Pipeline (ASP)



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Oleg Alexandrov, NASA Ames
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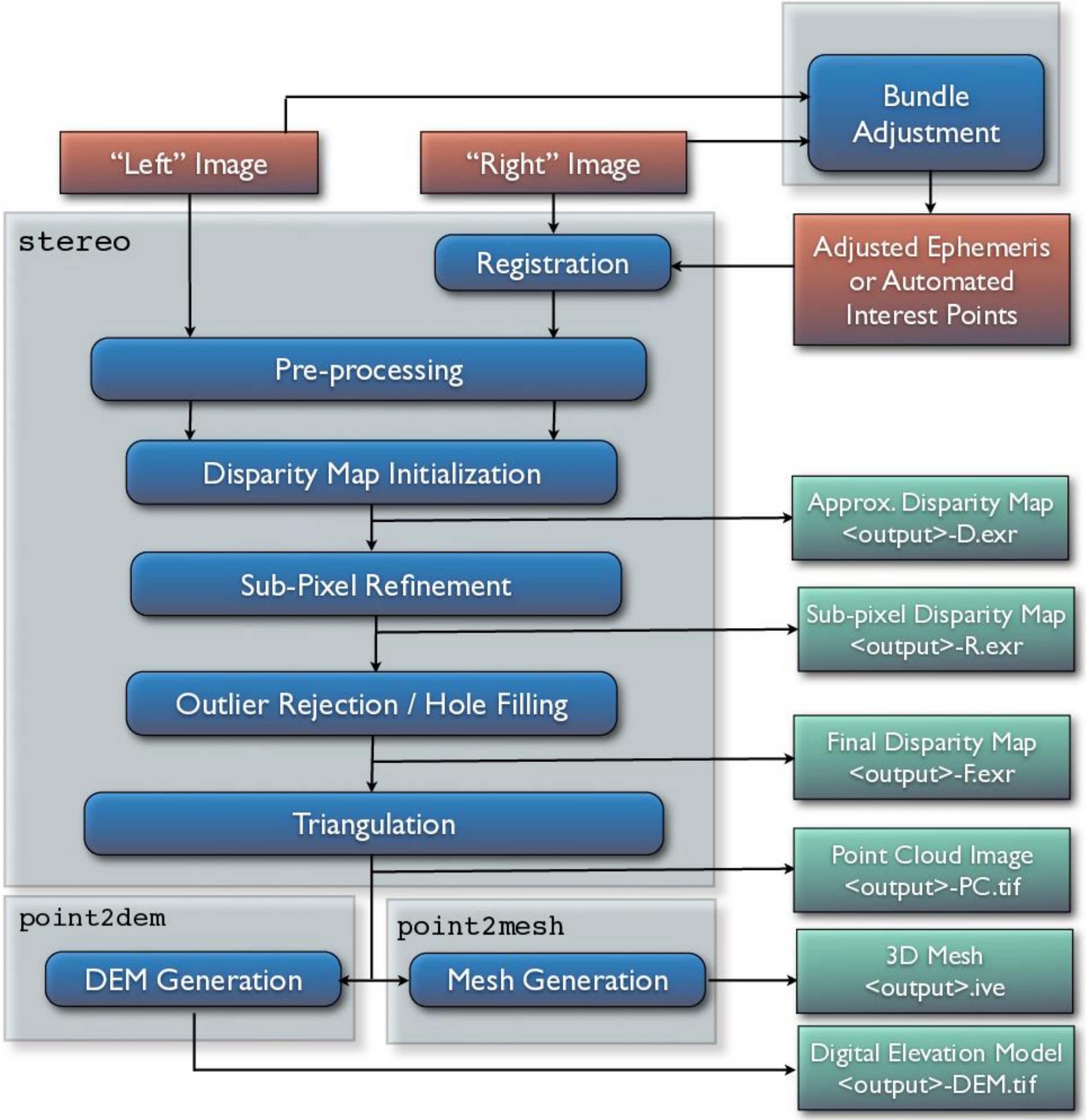
Topography

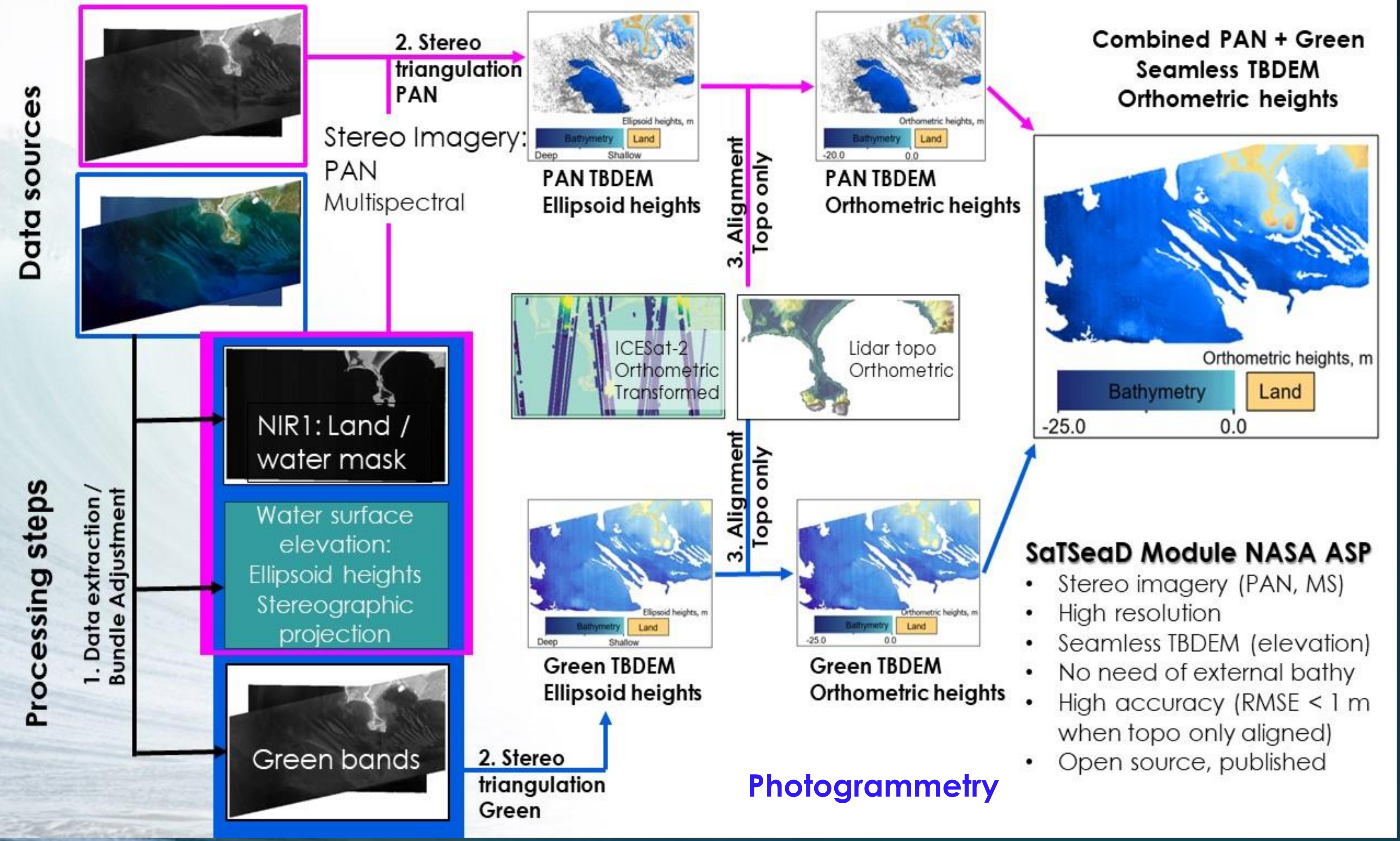
NASA Ames stereo pipeline (ASP)



Development

- Automated, open-source, command-line tools
- Developed initially for Mars Pathfinder (1997)
- NASA planetary orbiters (2008)
- Commercial Stereo (2012) – DigitalGlobe rigorous camera model
- RPC camera models (rational polynomial coefficients) added
- Skysat stereo (2019)
- Pleiades, Skysat video, USGSCSM Frame, SAR & Push Frame sensors, PeruSat-1 (2022)
- SaTSeaD (2022-23)
- C++ / Python, multithreaded, memory-efficient, scalable
- Binaries for Linux / OSX
- Source available on github
- Daily builds

ASP SaTSeaD Bathymetry module



- Bathymetry module – semi-active development
- Blue, Green and PAN bands
- Land/water mask (NIR1, NIR2, satellite index)
- Land/water thresholds:
  - KDE minima
  - Otsu
- Water elevation surface (local stereographic projection)
  - Interactive: Stereo GUI
  - Automatic: land/water mask
- Water refraction index:
  - General: 1.34, 1.33
  - Location specific: band wavelength, water temperature, water type
- 3D Reconstruction:
  - Topography
  - Bathymetry
  - Topobathymetry

Shallow water bathymetry SaTSeaD module

General Considerations

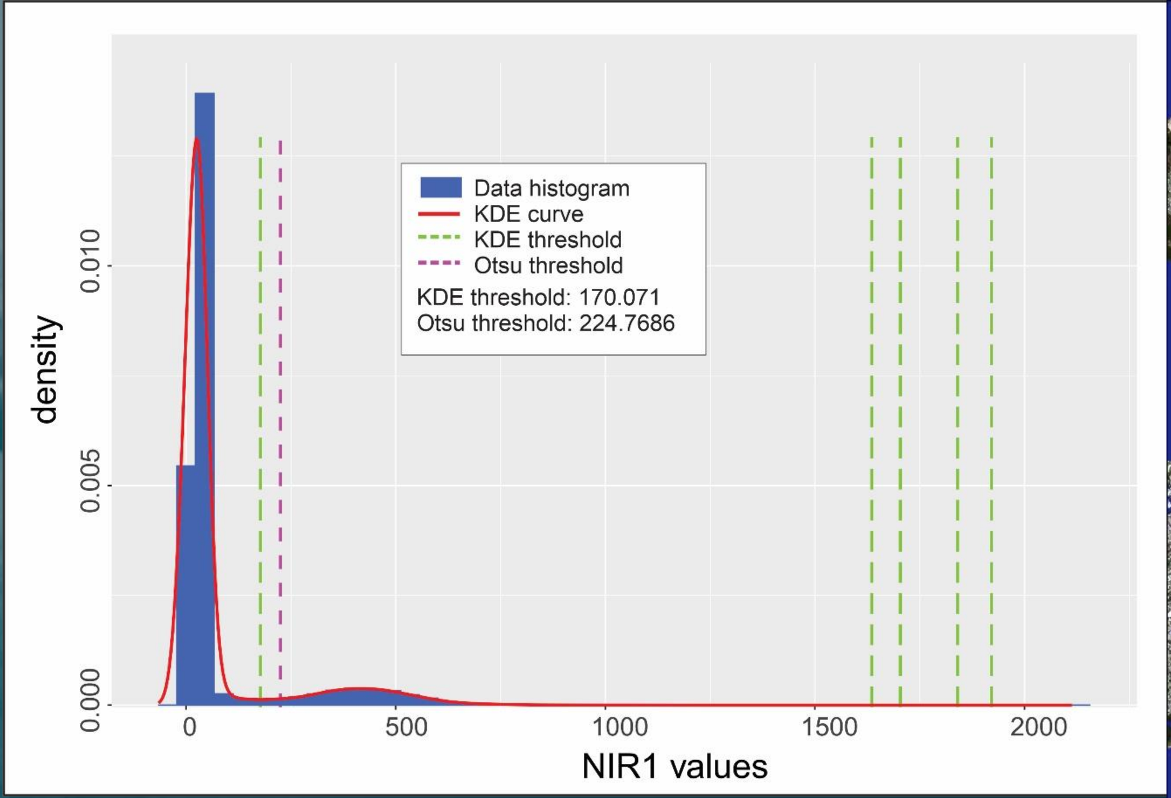
- Water is shallow, still, & clear
- Sufficient texture to match
- Converging rays refract at the water interface (Snell's law)
- Water elevation surface (ellipsoid heights)
- Rigorous camera models, RPC & pinhole cameras
- Raw and map-projected images
- Stereo: If pixel [image 1] in water & pixel [image 2] on land, then both pixels on land

Physics Considerations

- Shallow water does not appear equally transparent at all wavelengths
- Green or Blue bands have the deepest penetration theoretically
- Some dependency on location and environmental conditions
- Location dependent refraction coefficient
- DG PAN band for very shallow depths, but highest accuracy

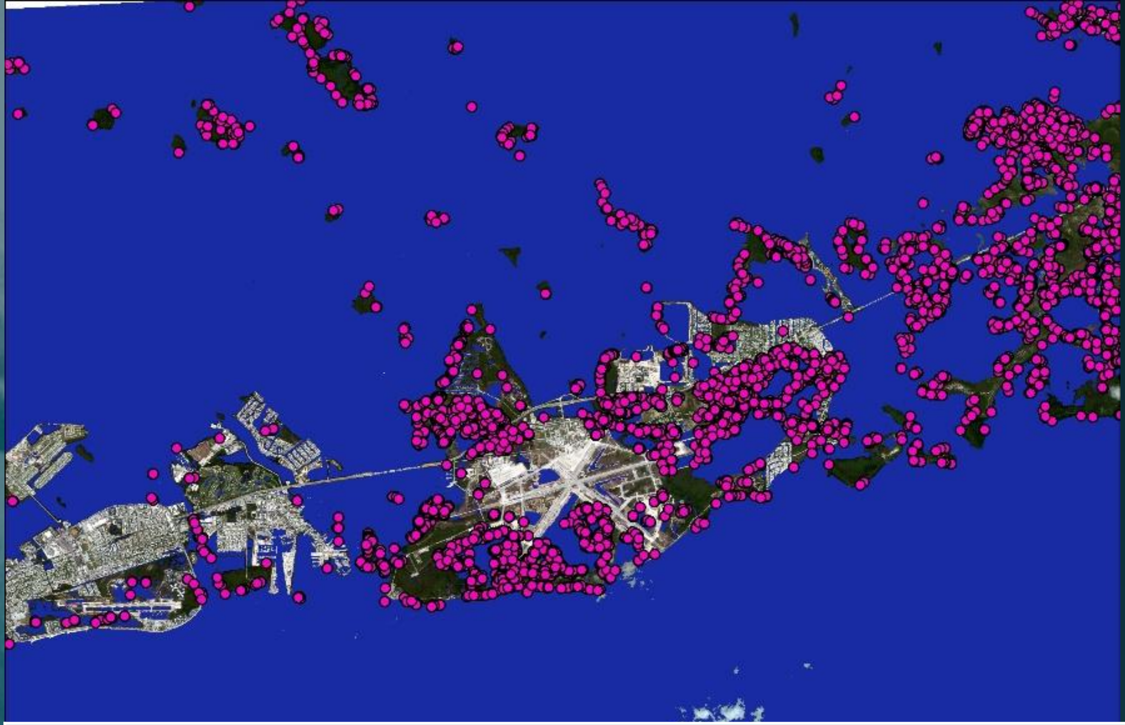
WV02 image, RGB band combination, FL Keys

Step 1. Land / water mask



- <u>KDE method:</u>
  - Image histogram analysis approx. by Gaussian kernels
  - Distribution of the land/water pixels is multimodal
  - More than one minima – user chooses the appropriate value
- <u>Otsu method:</u>
  - Minimizes the intra-class variance
  - Only one value
- <u>Land / water mask:</u>
  - Same dimensions as the stereo imagery used – rescale if using PAN instead of MS bands
  - Pixel values at or below the threshold changed to no-data
  - Pixel values above the threshold are not changed

Step 2. Water elevation surface

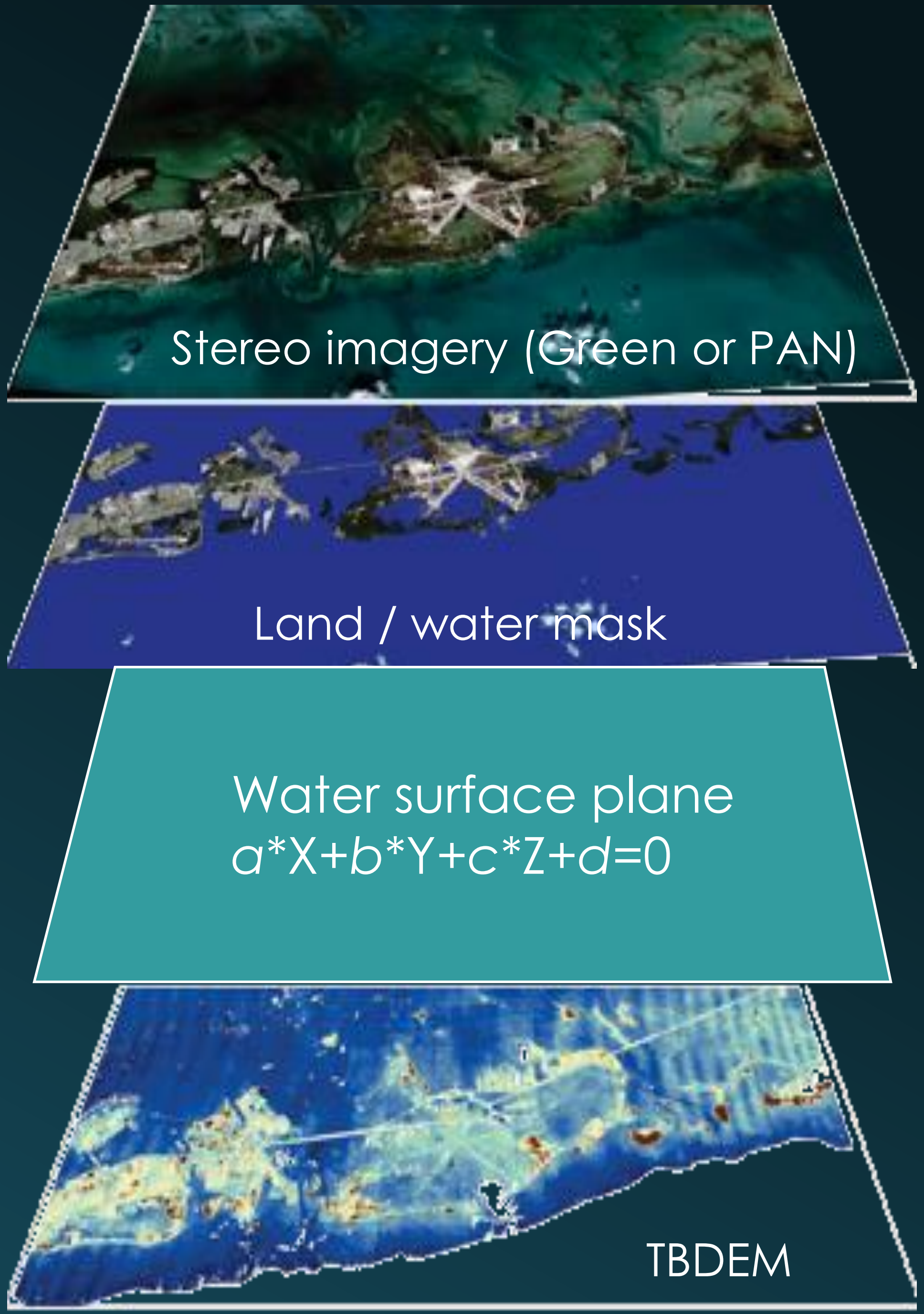


- Threshold needed for eliminating outliers – user defined
- External digital elevation model (DEM), camera information, and a land/water mask
- Table with water height measurements
- DEM and a point shapefile of x and y coordinates on the land/water limit
- <u>Tool saves:</u>
  - Water surface plane parameters as a text file: $a*X + b*Y + c*Z + d=0$
  - Shapefile of accepted inlier points and rejected outlier points for later inspection.

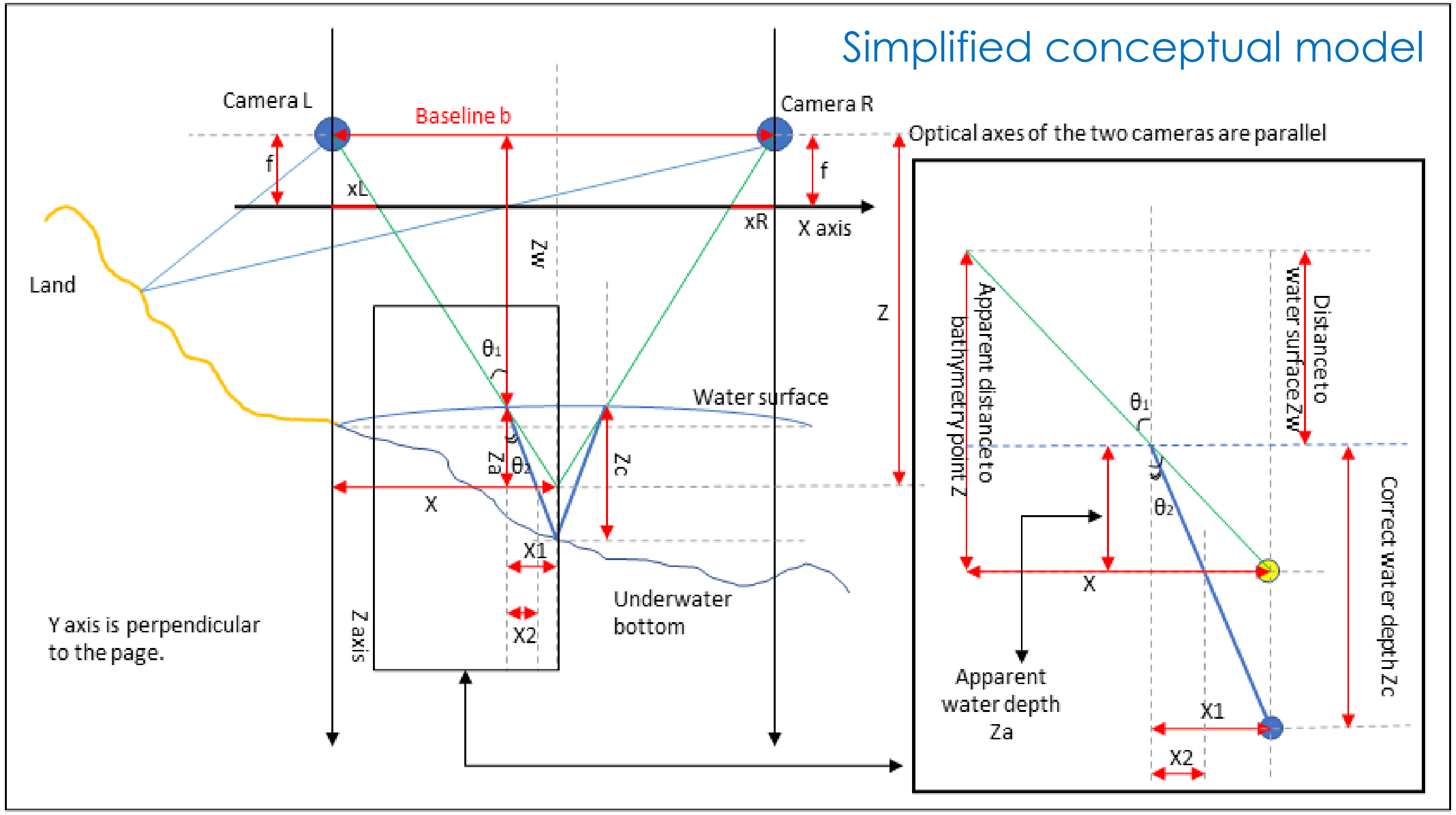
Left mask			
Mask type, parameters	WGS 1994 ellipsoid m	Mask type, parameters	WGS 1994 ellipsoid m
Otsu 0.2, 30k	-23.8932	KDE 0.2, 30k	-23.9418
Otsu 0.2, 300k	-24.0428	KDE 0.2 300k	-23.9519
Otsu 0.5, 30k	-24.0526	KDE 0.5, 30k	-24.0496
Otsu 0.5, 300k	-23.922	KDE 0.5, 300k	-23.9244
Right mask			
Mask type, parameters	WGS 1994 ellipsoid, m	Mask type, parameters	WGS 1994 ellipsoid, m
Otsu 0.2, 30k	-23.9379	KDE 0.2, 30k	-23.9004
Otsu 0.2, 300k	-23.9378	KDE 0.2 300k	-23.9221
Otsu 0.5, 30k	-24.0316	KDE 0.5, 30k	-24.0849
Otsu 0.5, 300k	-23.9959	KDE 0.5, 300k	-24.0187

Step 3. Stereo triangulation SaTSeaD module

- Main steps before triangulation:
  - Image alignment
  - Correlation
  - Sub-pixel refinement & filtering
- Camera metadata provides:
  - Camera parameters
  - Coordinates
  - Attitude
- Pre-requisites for SaTSeaD module:
  - Land/water masks – same resolution and extent as satellite images used
  - water surface plane – ellipsoid heights
  - Refraction coefficient
- Stereo reconstruction generates:
  - Combined topo-bathymetry (TBDEM) – the default
  - Topography
  - Bathymetry – elevation of submerged topography



Step 3. Stereo triangulation - 2



Eq. 1. $\frac{Z}{f} = \frac{X}{xL} = \frac{b-X}{xR} = \frac{Y}{yL} = \frac{Y}{yR}$

Eq. 2. $\frac{\sin(\theta 1)}{\sin(\theta 2)} = \frac{r}{r1}; r1 = 1$

Eq. 3. $tan(\theta 1) = \frac{X}{Z}; Za = Z - Zw; X1 = Za * tan(\theta 1) = \frac{X(Z-Zw)}{Z}$

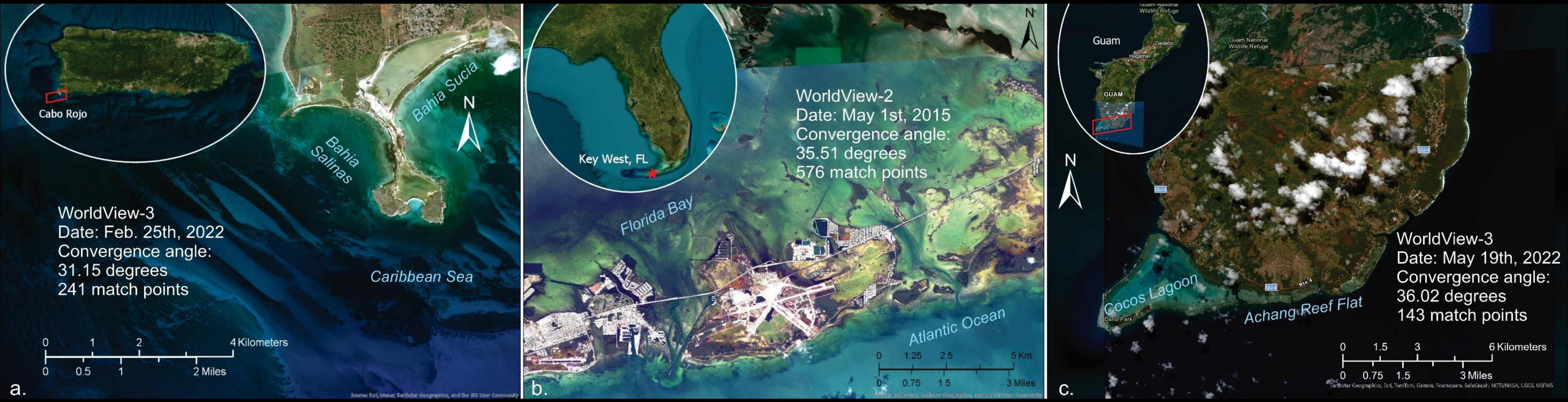
Eq. 4. $\sin(\theta 2) = \frac{\sin(\theta 1)}{r};\ X2 = Za * tan(\theta 2)$

Eq. 5. $\frac{Zc}{Za} = \frac{X1}{X2}; Zc = \frac{Za * X1}{X2} = \frac{Za * \tan(\theta 1)}{tan(\theta 2)}$

Eq. 6. $Zb = water\ elevation - Zc$

- b = distance between cameras, baseline
- f = focal length
- xR, xL = distance on X axis between the cameras (L=left, R=right) and their respective triangulation rays at focal length
- Z = apparent distance to bathymetry point on Z axis, no refraction correction
- Zw = distance to water surface on Z axis
- Za = apparent water depth, no refraction correction
- Zc = corrected water depth after refraction correction
- Zb = corrected bathymetric elevation
- X = distance on X axis between camera and bathymetric point; in this ideal case both the apparent and corrected bathymetric points are on same vertical.
- X1 = distance on X axis between the point where the ray intersects the water surface and the apparent bathymetric point, no refraction correction
- X2 = distance on X axis between the point where the ray intersects the water surface and the corrected bathymetric point, refraction correction applied
- θ1 = angle of incidence between the ray and vertical when intersecting the water surface
- θ2 = angle of refraction
- r1 = refractive index in medium 1; r1 = 1.
- r = refractive index in medium 2; in this case ocean water refractive index.

Data



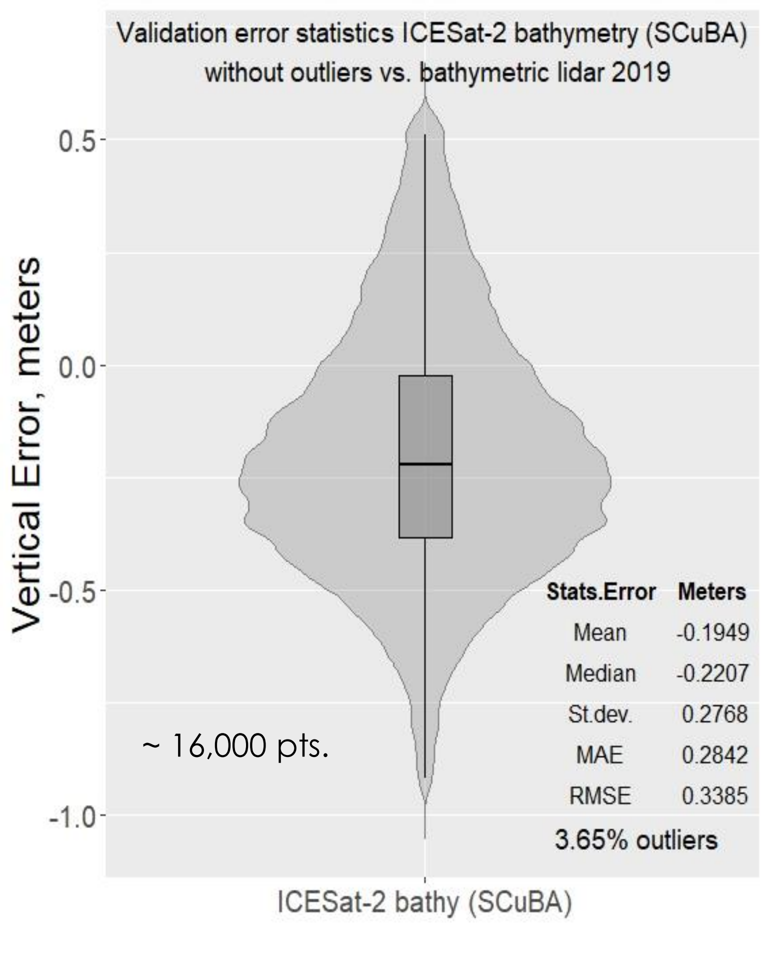
Cabo Rojo,
Puerto Rico

Key West, Florida

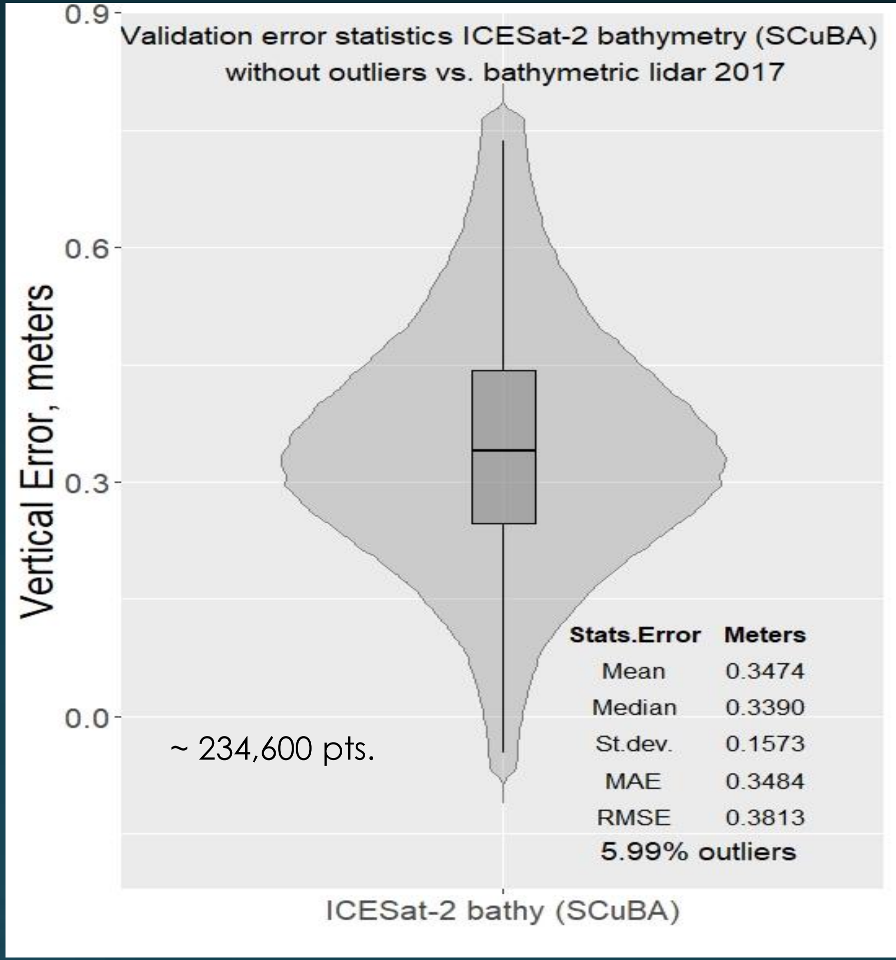
Cocos Lagoon and reef flat
Guam

ICESat-2 bathymetry
SCuBA: Satellite Computed Bathymetry Assessment

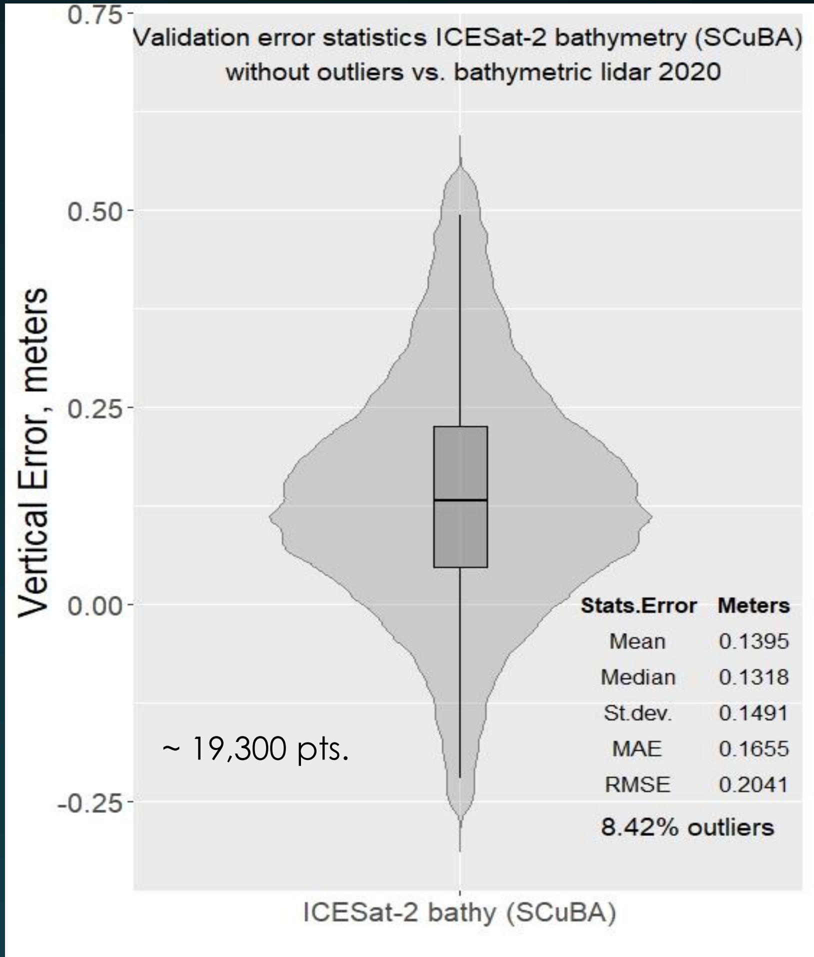
Puerto Rico



Florida Keys



Guam



NOAA / NGA Satellite Computed Bathymetry Assessment-SCuBA data were accessed from https://registry.opendata.aws/noaa-nos-scuba-icesat2-pds.

Results: Cabo Rojo, Puerto Rico Photogrammetry (SaTSeaD)

- ICESat-2 bathy data (NGA SCuBA) **Max. depth: -20.5m**

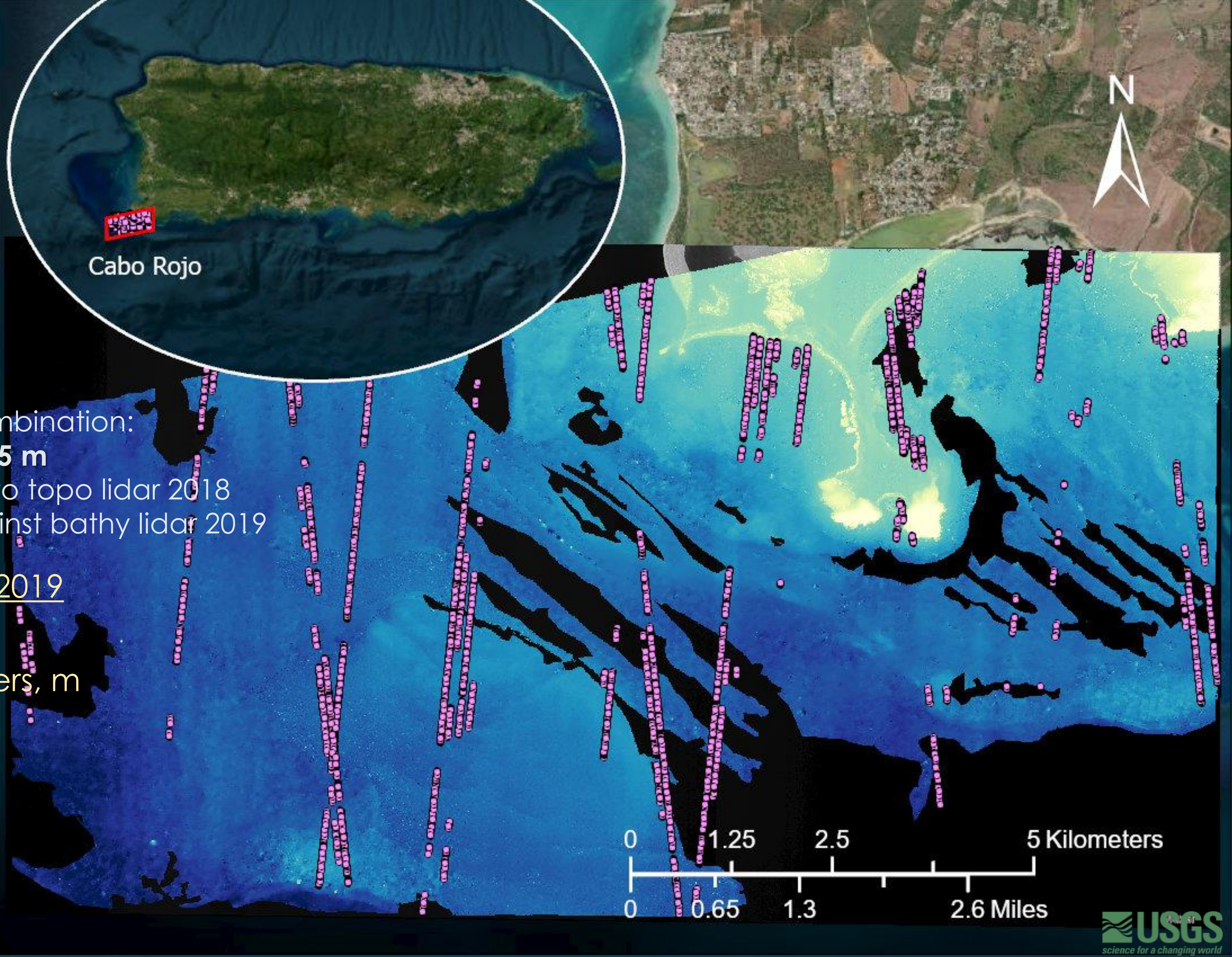
PAN & GRN Band combination:
Depth penetration: -25 m
Topography aligned to topo lidar 2018
Bathy validation: against bathy lidar 2019

Validation vs. lidar 2019
> 18 mil. Points

Stats. Error, no outliers, m

Mean	-0.4058
Median	-0.3482
St.dev.	0.7836
MAE	0.6875
RMSE	0.8824

% outliers: 3.5%



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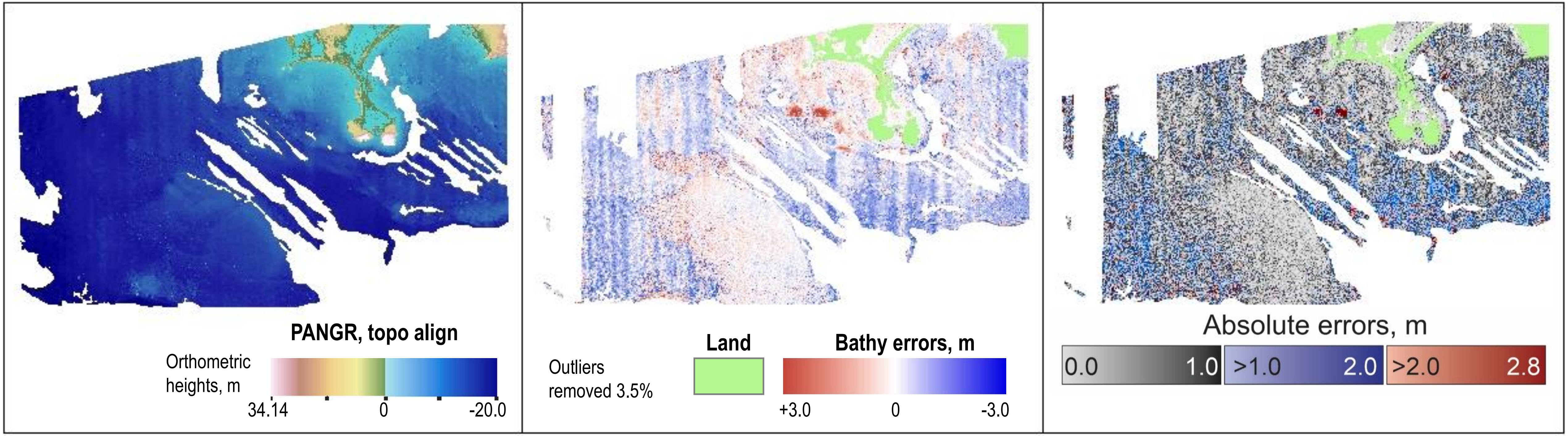
Bahia Salinas: PAN-GRN Band Topobathy & Validation



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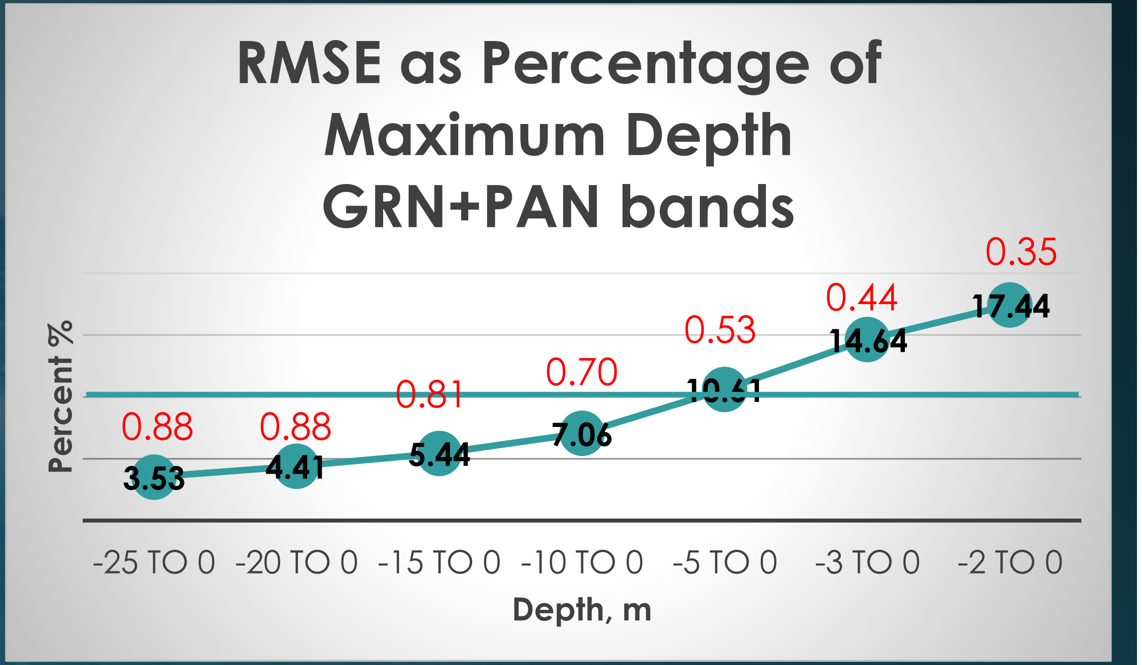

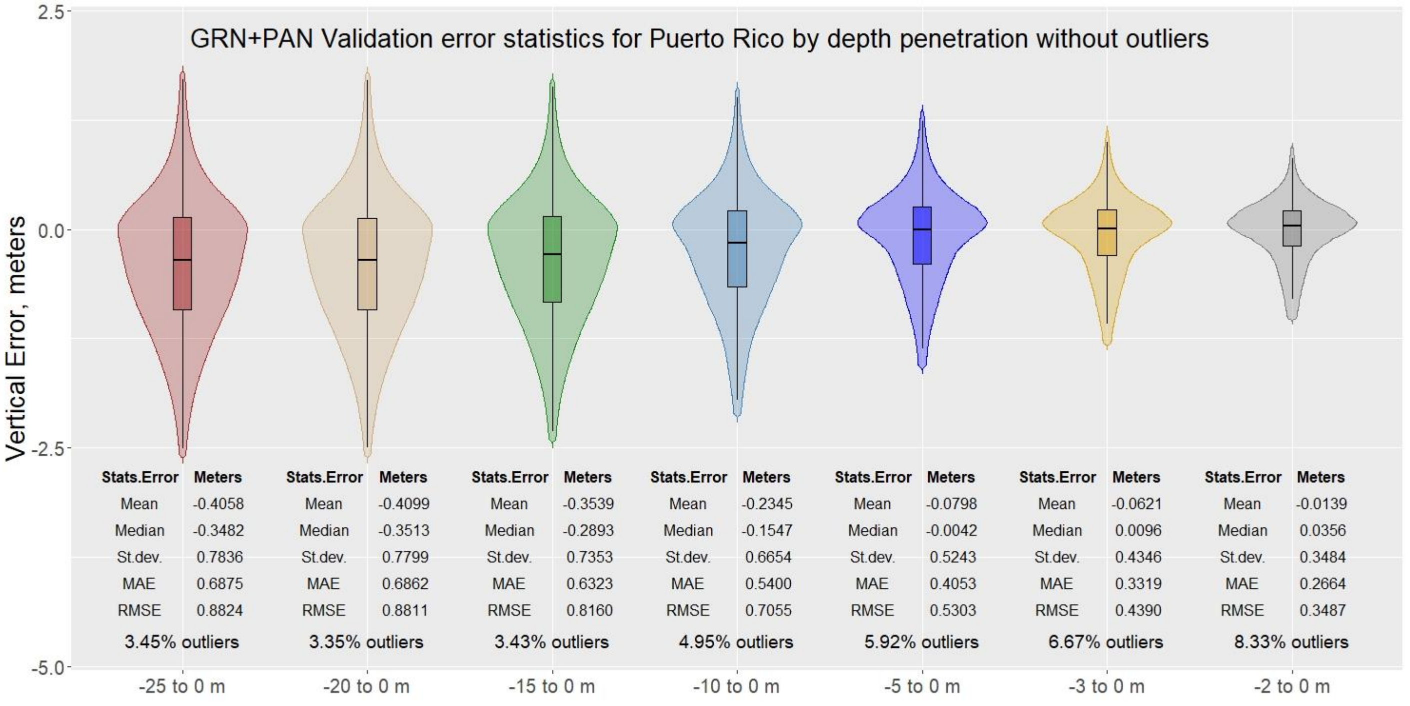

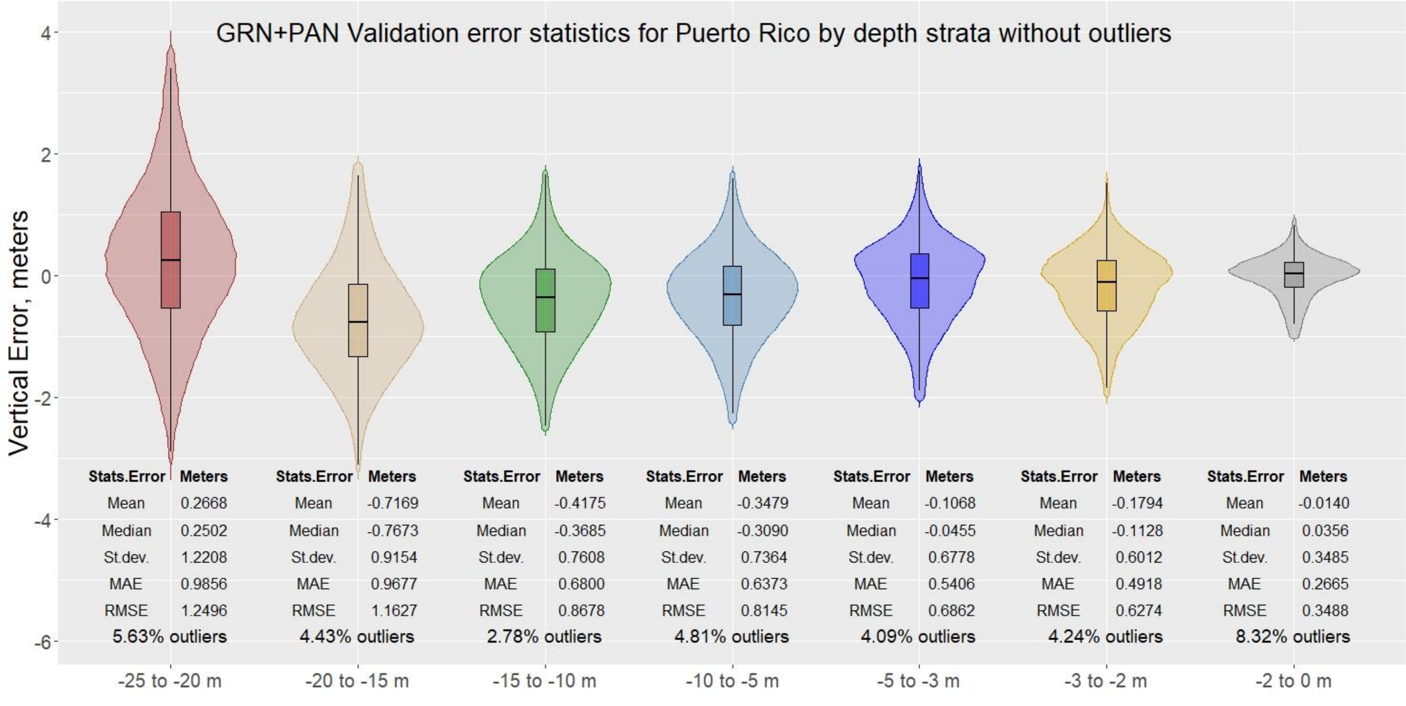

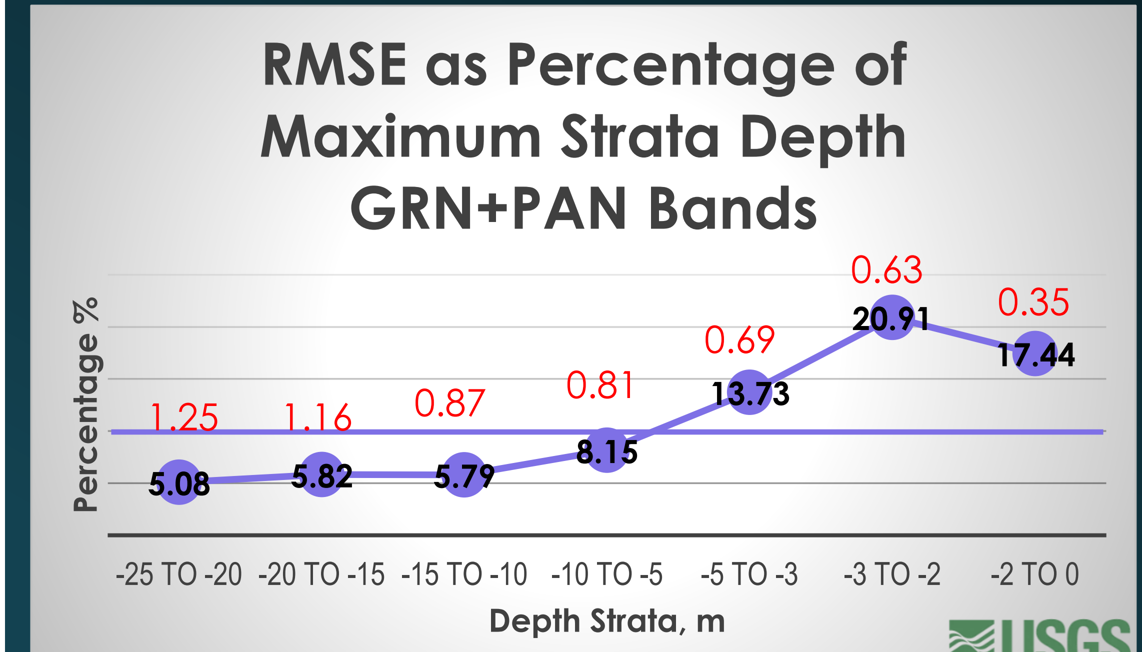

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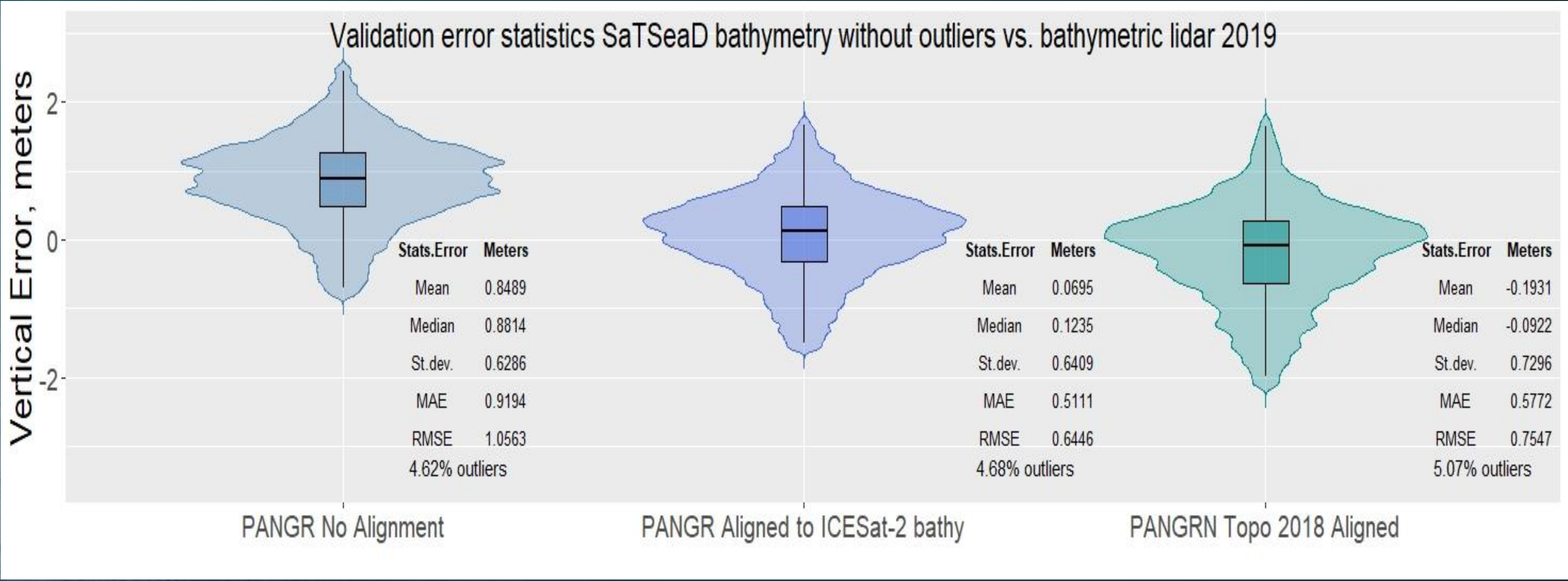
Cabo Rojo, PR: Bathymetry validation on ICESat-2 bathymetry point locations: ~ 16,000 points



Results: Key West, FL Photogrammetry (SaTSeaD)

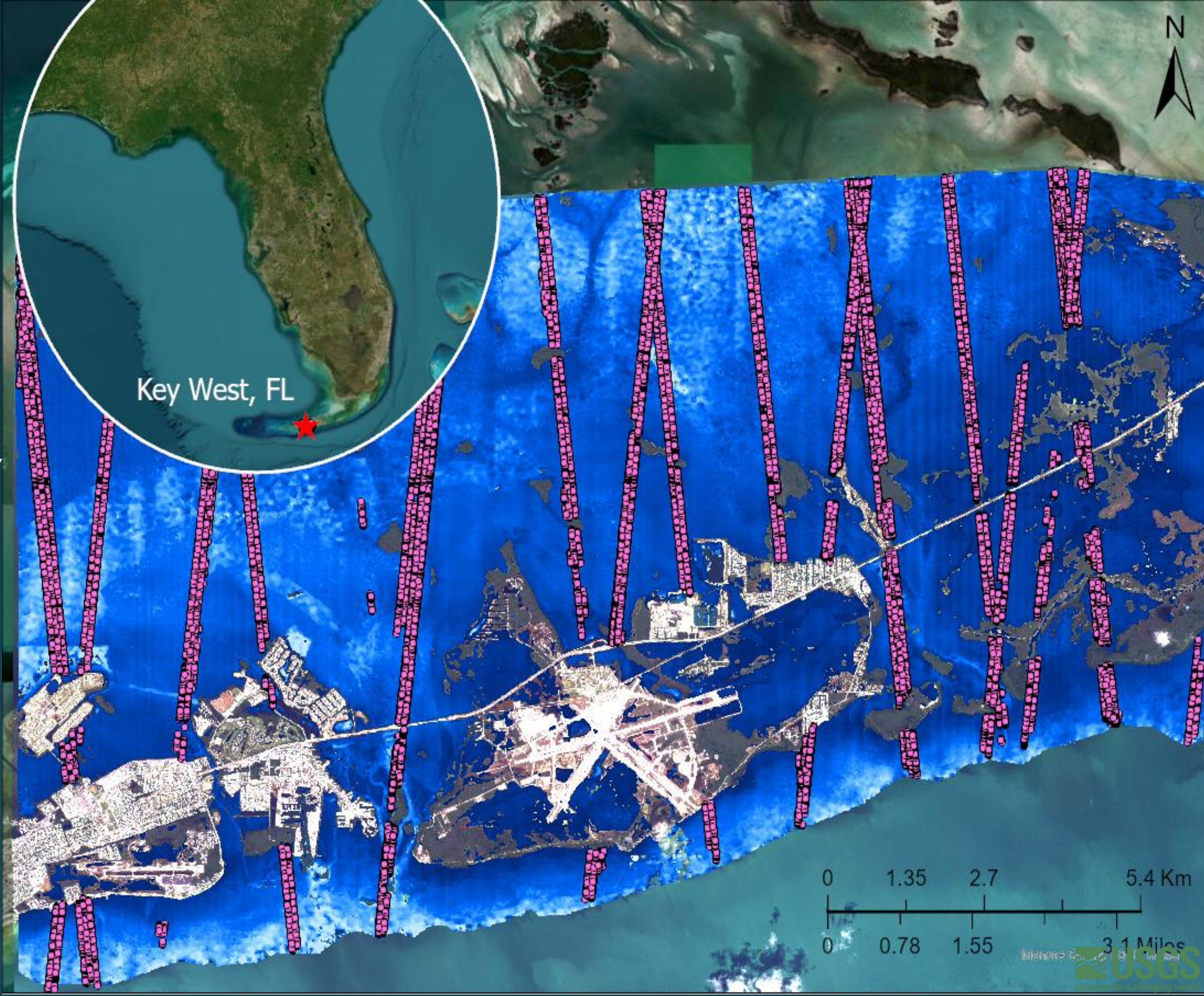
ICESat-2 bathy data (NGA SCuBA)
Max. depth: -6.7m

PAN & GRN Band combination
Depth penetration: -7 m
Aligned to topo lidar 2017
Bathy validation: bathy lidar 2017

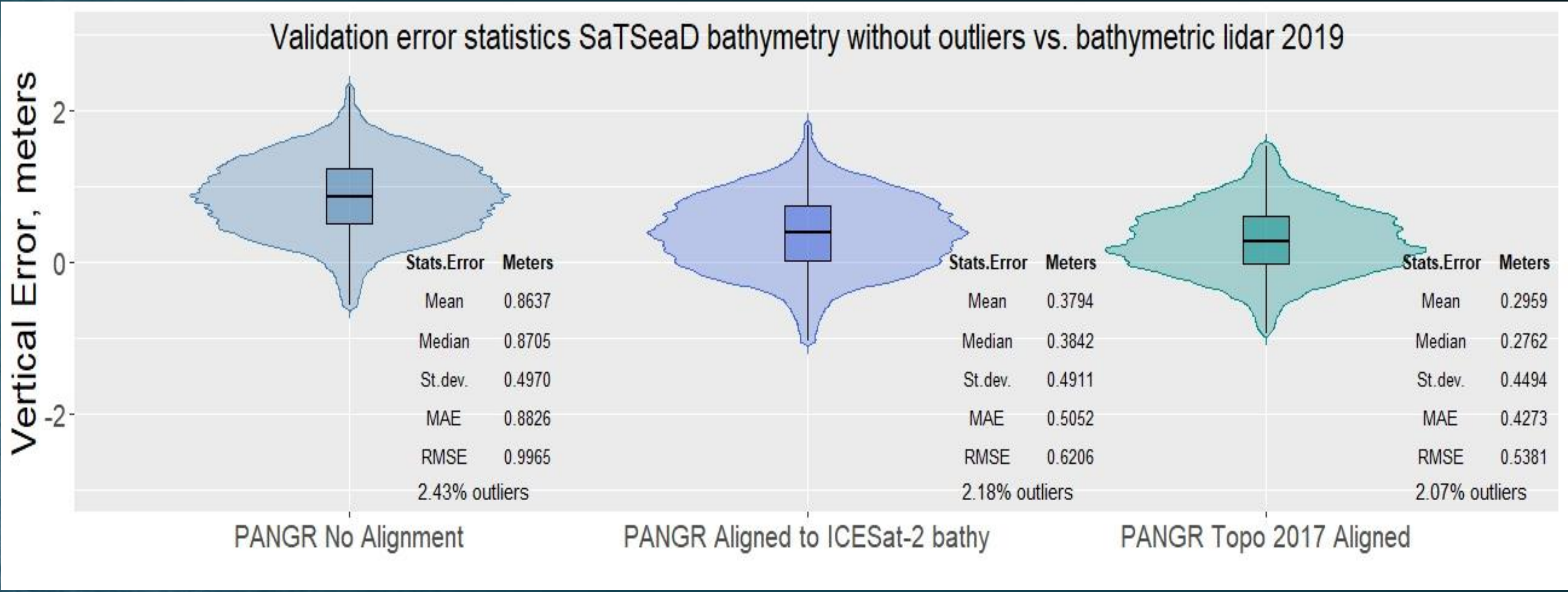
<u>Validation vs. lidar 2017</u>
> 4 mil. points

Stats. Error, no outliers, m	
Mean	0.2401
Median	0.2348
St.dev.	0.5241
MAE	0.4564
RMSE	0.5765

% outliers: 6.87%



Key West, FL: Bathymetry validation on ICESat-2 bathymetry point locations: ~ 234,600 points



Results: Guam Photogrammetry (SaTSeaD)

ICESat-2 bathy data (NGA SCuBA)
Max. depth: -13m

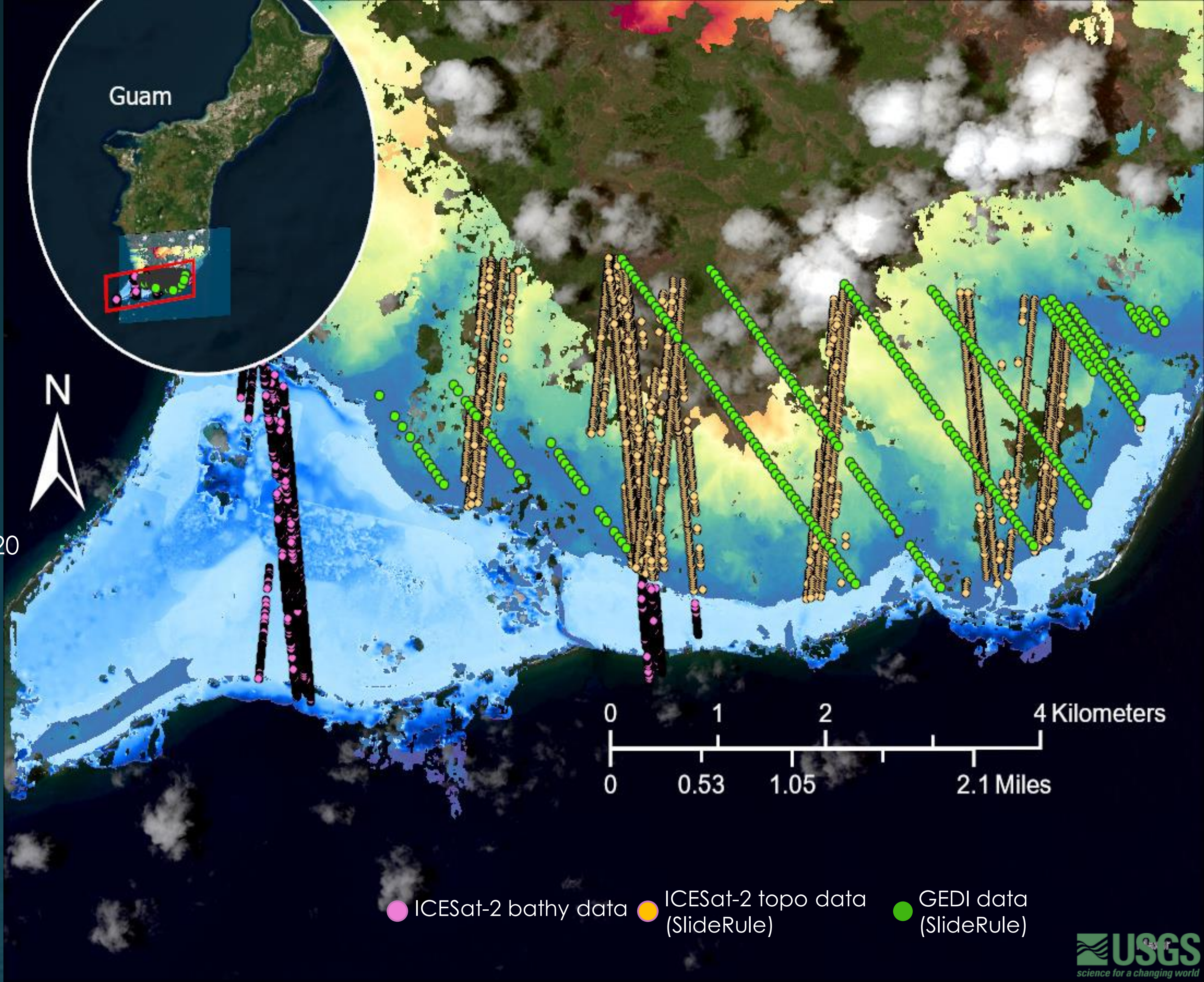
PAN & GRN Band combination
Depth penetration: -25 m
Aligned to topo lidar 2020
Bathy validation: bathy lidar 2020

<u>Validation vs. lidar 2020</u>

> 3.5 mil. points

Stats. Error, no outliers, m

Mean	0.0376
Median	-0.0866
St.dev.	0.5841
MAE	0.4314
RMSE	0.5853
% outliers:	17.67%



Conclusions

- Photogrammetric SDB method independent of external bathy data:
  - First open-source: NASA ASP SaTSeaD
  - Single method to generate a seamless integrated TBDEM
  - Can take advantage of PAN stereo data accuracy
- Maximum depth penetration depends on water clarity
  - ~0 to ~30 (optical imagery); ~1 Secchi Disk for MS data, ~0.3 – 0.4 Secchi Disk for PAN
- Resolution: depends on satellite image resolution
- Accuracy: depends on method/parameters used and water conditions
  - **SaTSeaD:** Accuracy of land/water mask and surface water elevation modelling (tides)
  - Bundle adjustment and alignment to high-accuracy external subaerial topography data increases bathy accuracy substantially
  - PAN bathy results are more accurate, but have less depth penetration and/or extent than Green band results
  - Bathymetry validation error outliers mostly around no-data voids
- Validation RMSE decreases with water depth reduction, but the percentage of RMSE relative to max. depth water interval increases with water depth reduction
- Track bathymetry data from satellite: ICESat-2 (green lidar) - SCuBA
  - ~2.7 – 3 km between 3 pairs, ~ 90 m between R and L of each track pair, ~ 0.7 m distance between points along track.
  - Bias vs. bathy lidar -0.2 to 0.3 m, RMSE: 0.2 – 0.4 m; Depends on location
- Refraction coefficient is important for accurate bathymetry
  - Up to ~25% increased error for lidar bathymetry; up to ~33% increased error for stereo bathymetry

References:

Palaseanu-Lovejoy, M.; Alexandrov, O.; Danielson, J.; Storlazzi, C. SaTSeaD: Satellite Triangulated Sea Depth Open-Source Bathymetry Module for NASA Ames Stereo Pipeline. Remote Sens. 2023, 15, 3950. https://doi.org/10.3390/rs15163950

SaTSeaD user manual: https://stereopipeline.readthedocs.io/en/latest/examples/bathy.html

NASA ASP: https://github.com/NeoGeographyToolkit/StereoPipeline/releases

NOAA / NGA Satellite Computed Bathymetry Assessment-SCuBA https://registry.opendata.aws/noaa-nos-scuba-icesat2-pds

ICESat-2 ATL06 SlideRule: https://slideruleearth.io/web/rtd/