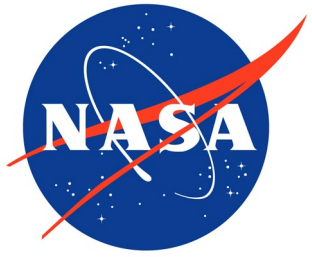
ATL24: A New Global ICESat-2 Bathymetric Data Product

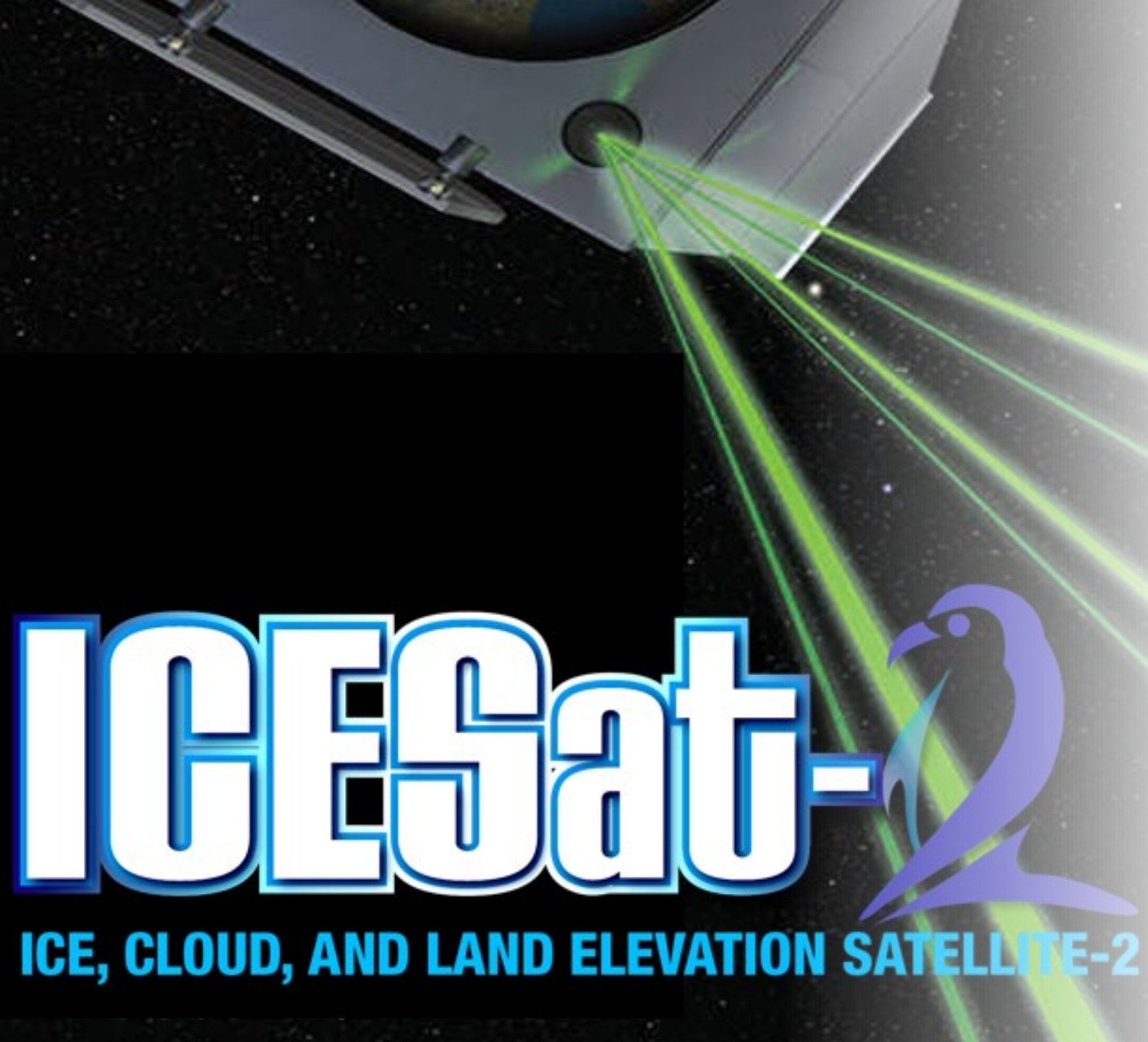
Christopher Parrish, Lori Magruder, Jeff Perry, J.P. Swinski, Matthew Holwill, Keana Kief, and Forrest Corcoran

NASA Earthdata Webinar
April 9, 2025



The University of Texas at Austin
Center for Space Research
Cockrell School of Engineering

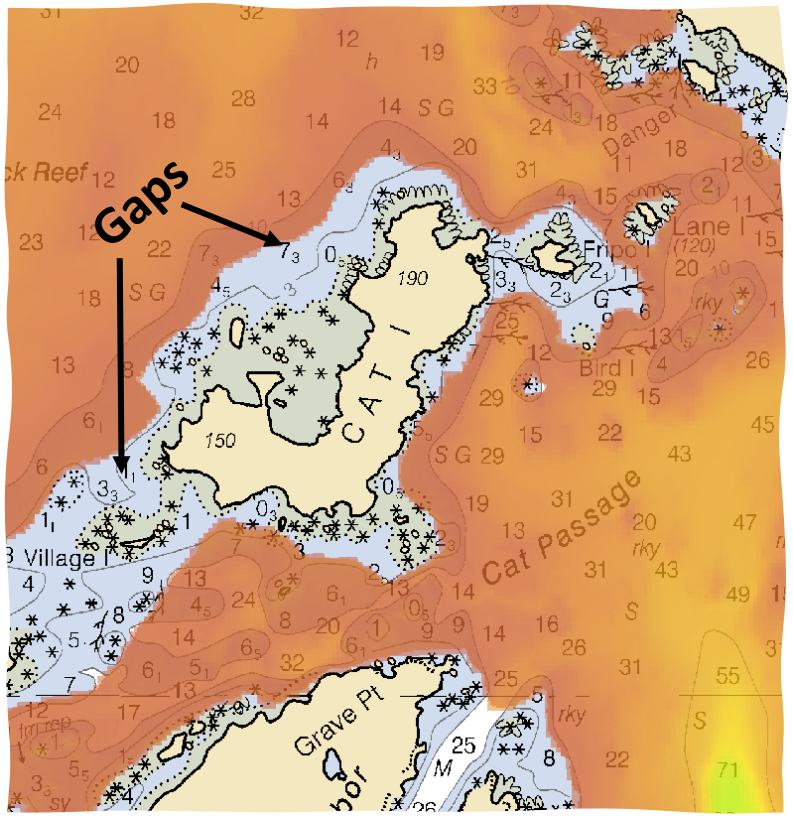
Oregon State University

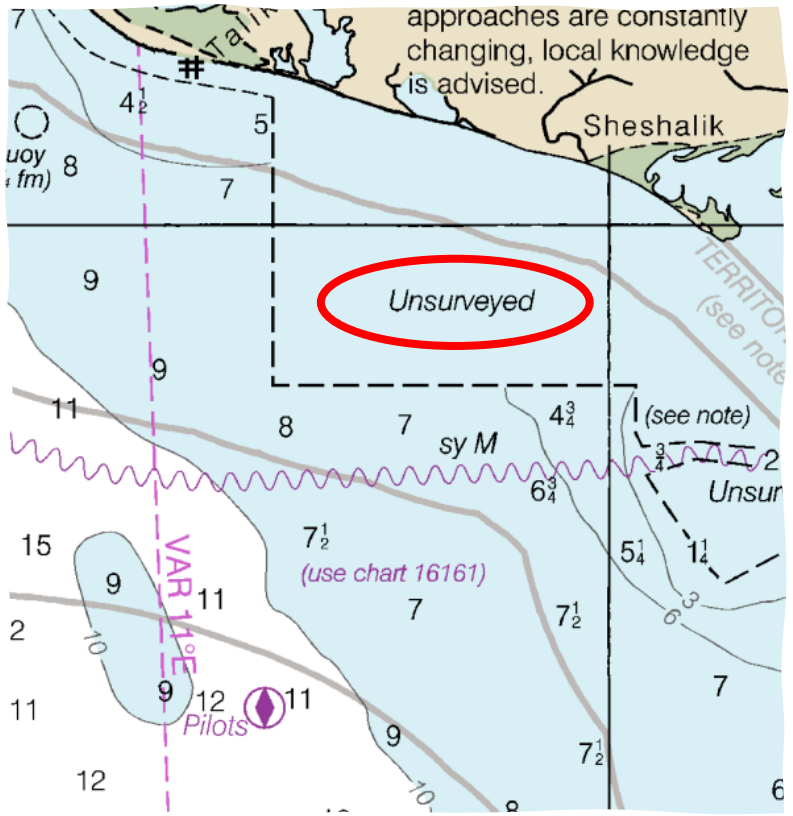


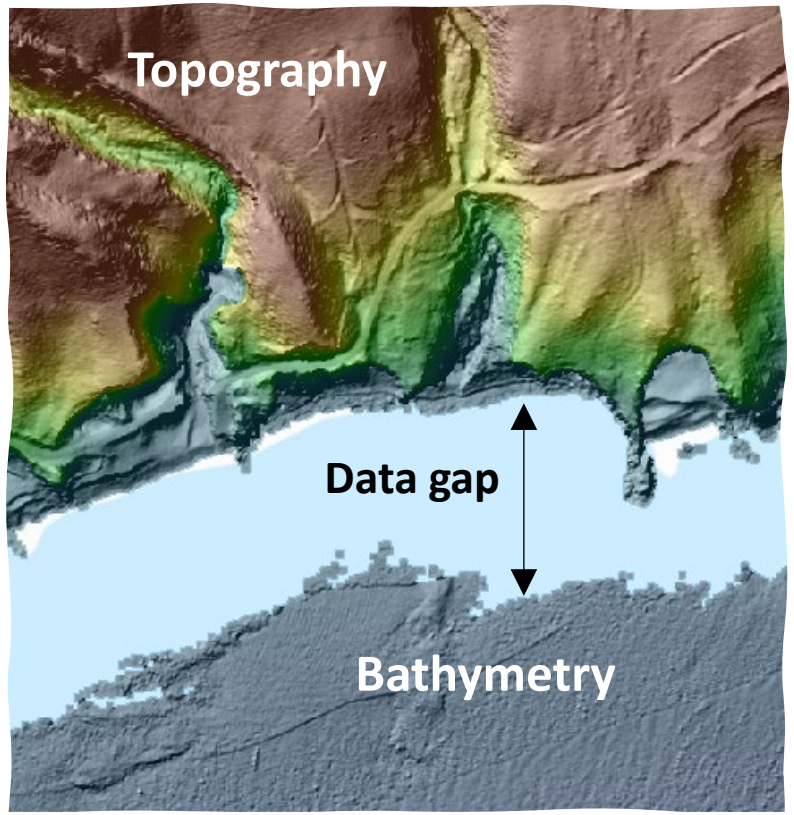
NASA's ICESat-2

- Launched September 15, 2018, as successor to original ICESat
- Has now been on-orbit collecting data for > 6.5 years
  - 2 trillion laser shots (and counting)
- 496-km orbital altitude
- Single sensor: photon-counting, green-wavelength lidar: ATLAS
- Designed for cryospheric science (ice sheets, glaciers, sea ice), as well as vegetation heights
- Also quickly gained recognition as world's *first spaceborne bathymetric lidar*

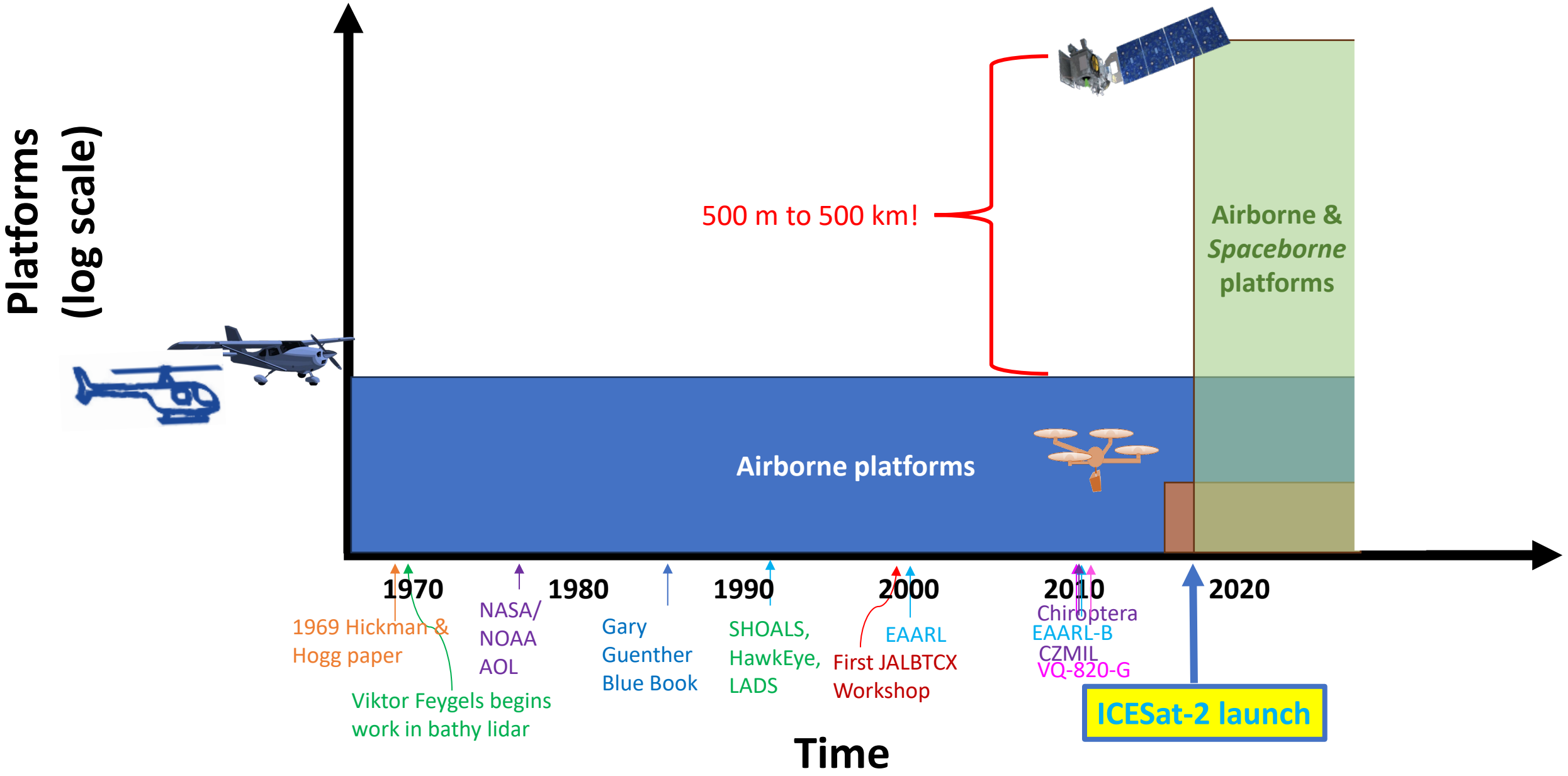
Addressing the global nearshore data void





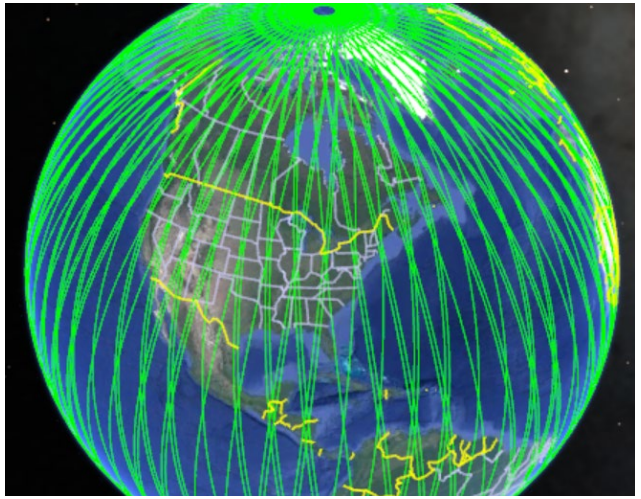


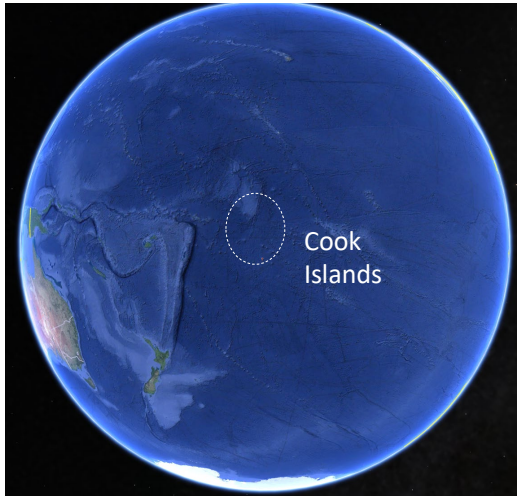
Bathymetric Lidar – an Abbreviated History/Timeline

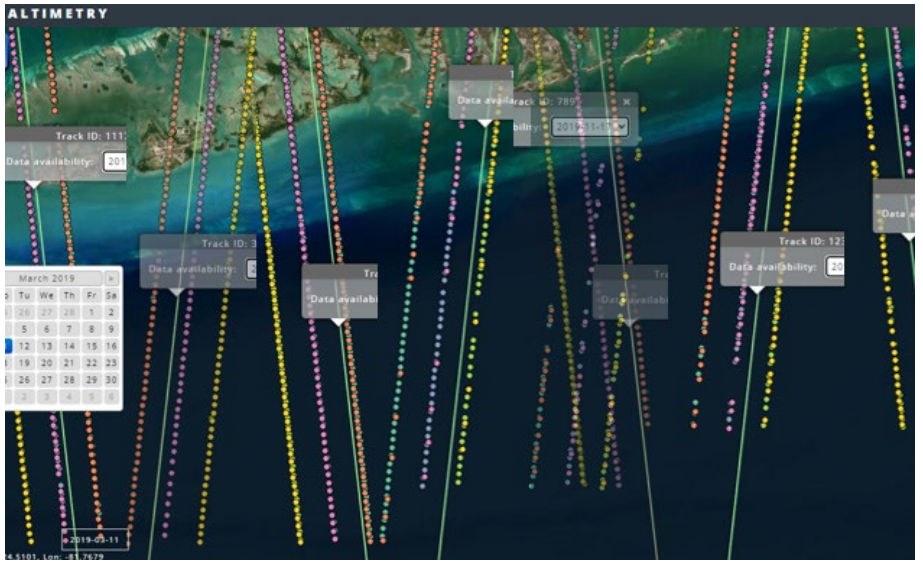


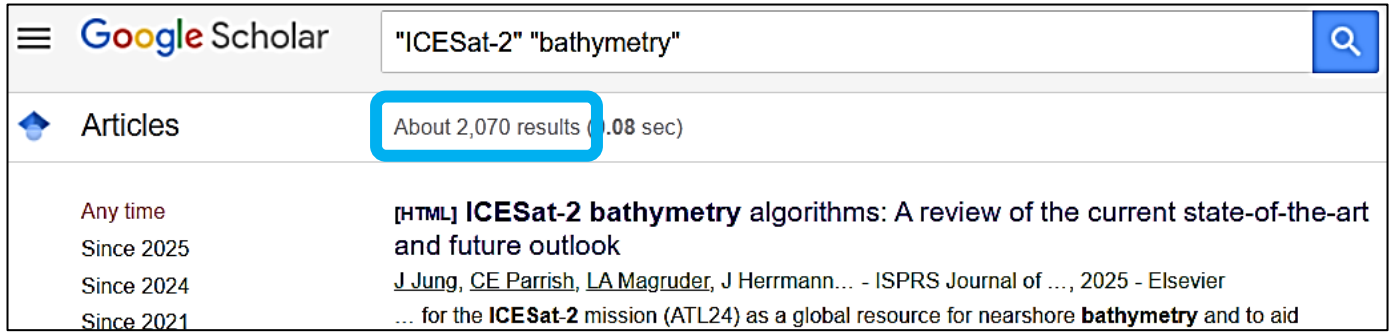
Why Space-Based Bathymetric Lidar is a Big Deal

- Near global coastal coverage: 88° S to 88° N
- Lots of revisit opportunities
  - Helpful for filling in voids in areas that are frequenty turbid
  - Increasing coverage over time
- Freely-available to users
- Highly complementary with bathymetry from multispectral imagery (e.g., Sentinel-2 and Landsat 9)
- Has opened up an entirely new field of study!

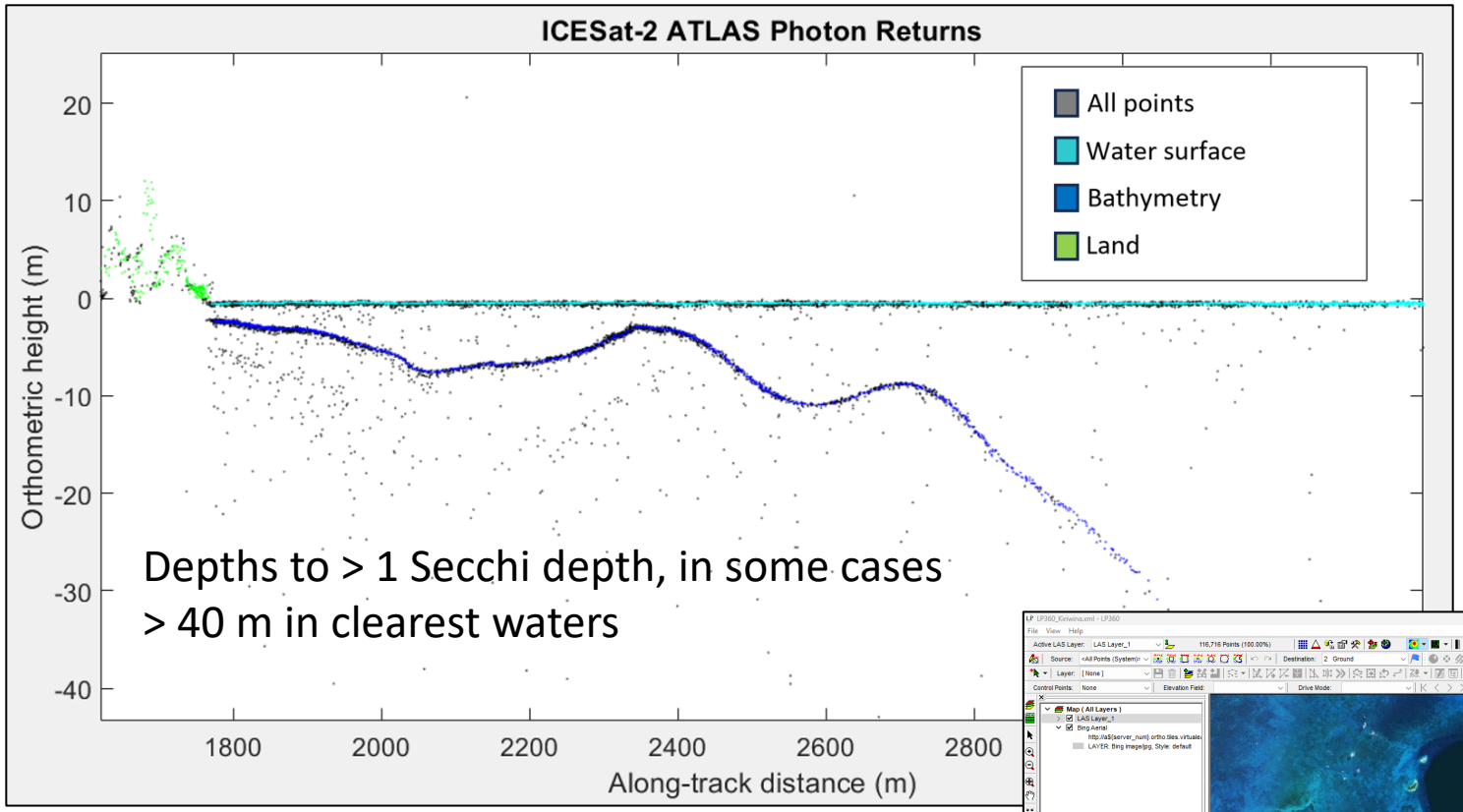


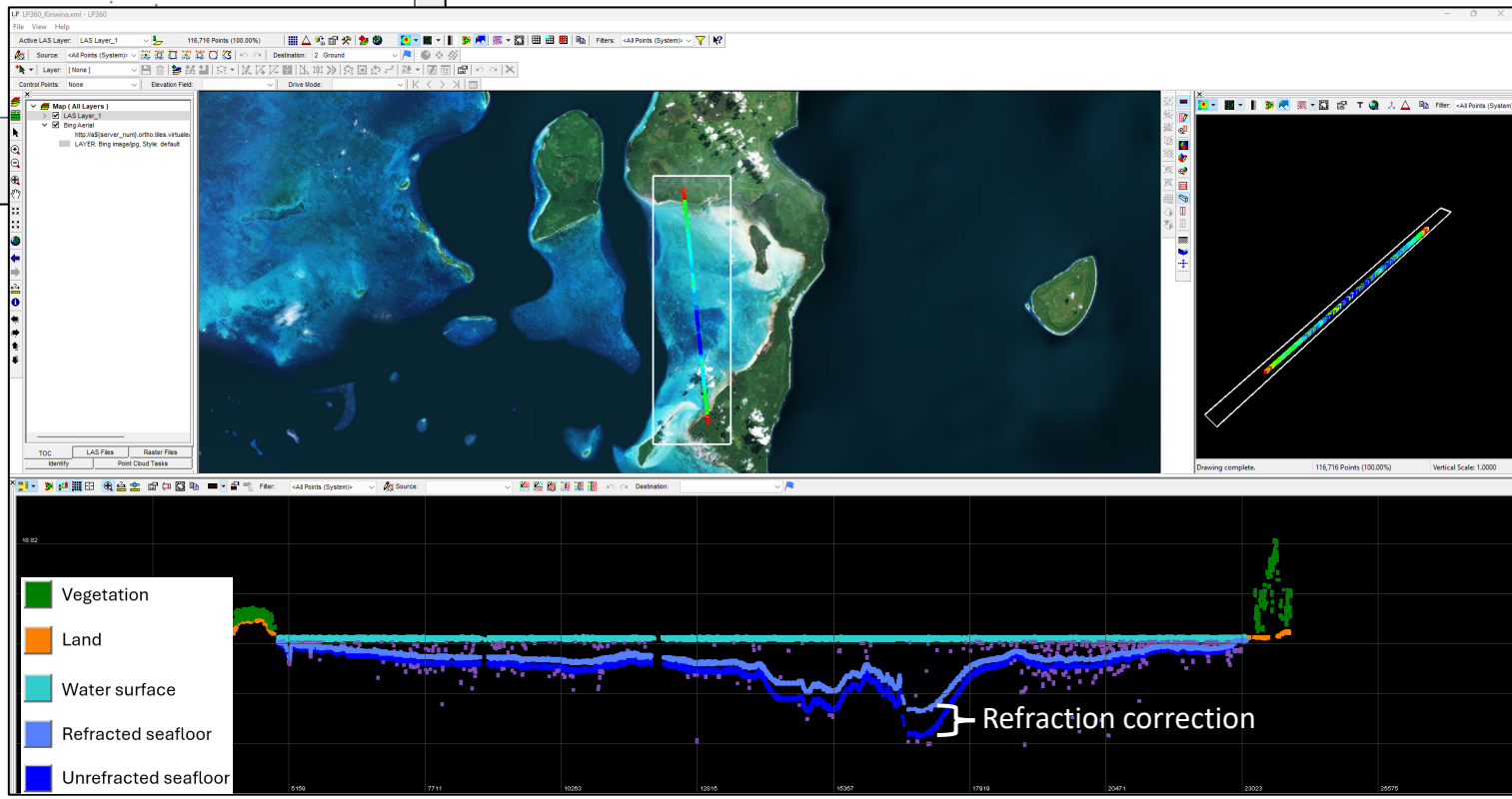






Examples of ICESat-2 Bathymetry

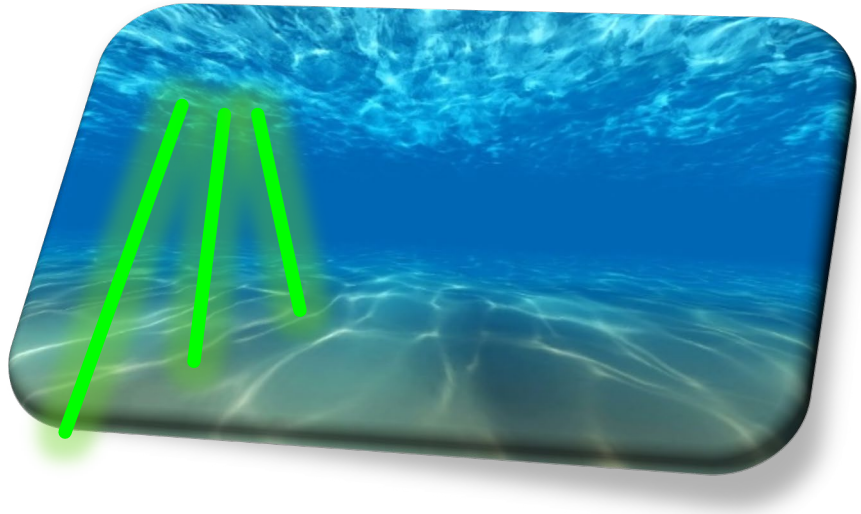




Jung, J., C.E. Parrish, L.A. Magruder, J. Herrmann, S. Yoo, and J.S. Perry, 2025. ICESat-2 bathymetry algorithms: A review of the current state-of-the-art and future outlook. *ISPRS Journal of Photogrammetry and Remote Sensing*, Vol. 223, pp. 413-439: https://www.sciencedirect.com/science/article/pii/S0924271625001145

Dietrich, J.T., and C.E.Parrish, 2025. Development and Analysis of a Global Refractive Index of Water Data Layer for Spaceborne and Airborne Bathymetric Lidar. *Earth and Space Science*, 12(3): https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2024EA004106

Coastal and Nearshore Along-Track Bathymetry Product (ATL24)



- Dedicated Coastal and Nearshore Along-Track Bathymetry Product
- Supported by ICESat-2 PSO as part of extended mission
- Provides
  - Global photon-level classifications of seafloor and sea surface using ensemble ML model
  - Classification confidence values
  - Refraction-corrected seafloor elevations
  - Per-point uncertainty estimates

Amazing Team
UTA: Lori Magruder (UT PI), Jeff Perry, Matt Holwill, Jonathan Markel
OSU: Chris Parrish (OSU PI), Keana Kief, Forrest Corcoran
NASA GSFC: JP Swinski

ATL24 *Simplified* Workflow

ATL03 granules (ICESat-2 geolocated photon data)

Preprocessing

CoastNet water surface classification

Bathymetry classification algorithms/ models:

- OpenOceans++
- CoastNet
- Median filter
- BathyPathfinder
- C-SHELPh
- Local contrast
- PointNet++ (not used in Rel 01)

Ensemble (XGBoost)

Classifications and confidence

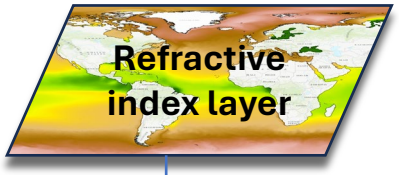
Blunder detection

Final sea surface finding

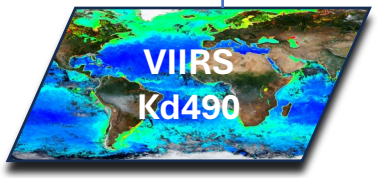
Refraction Correction

Uncertainty calculation

Data product generation



Subaqueous uncertainty LUTs



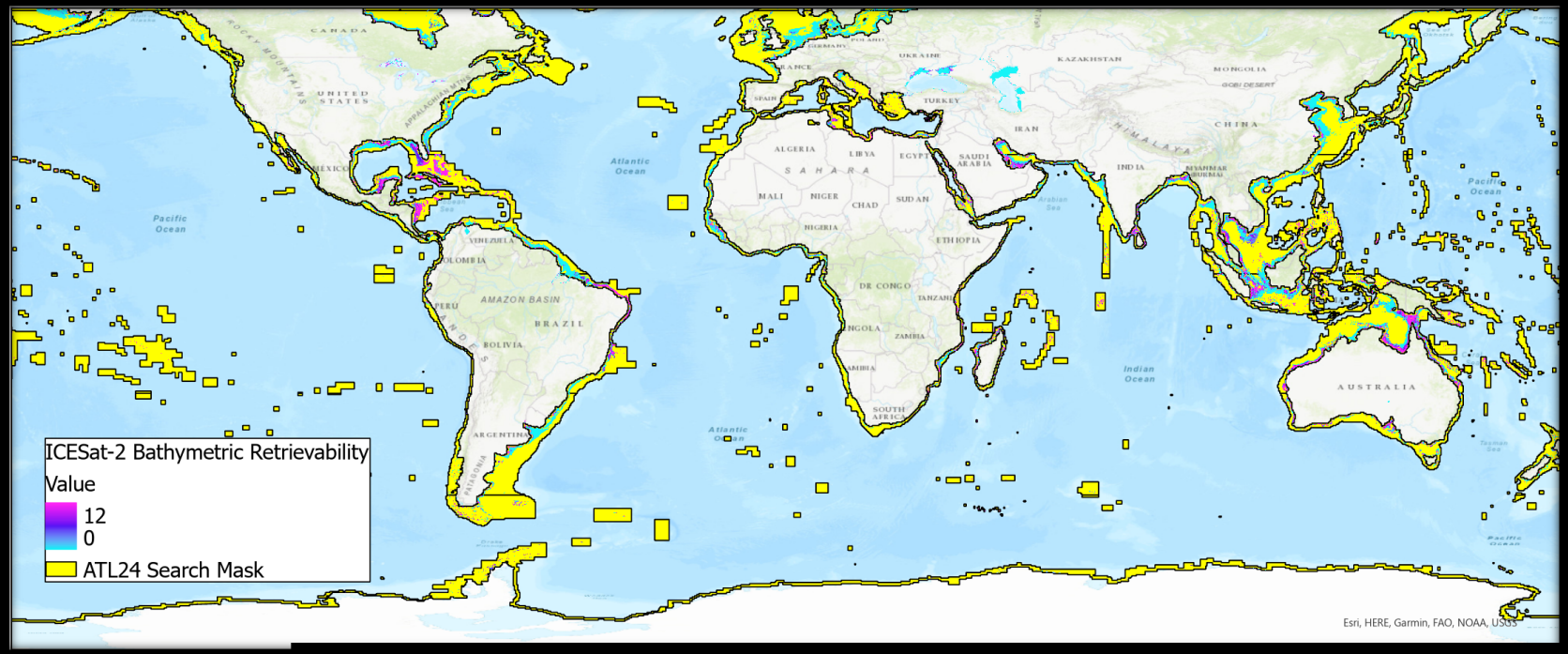
ATL24 data product

- Seafloor ellipsoid height
- Seafloor orthometric height
- ASPRS point classification (0, 40, 41)
- Uncertainty estimates
- Ensemble confidence

L.A. Magruder, C. Parrish, J. Perry, M. Holwill, J.P. Swinski, and K. Kief, 2025. ICESat-2 coastal and nearshore bathymetry product algorithm development. *ESS Open Archive*.

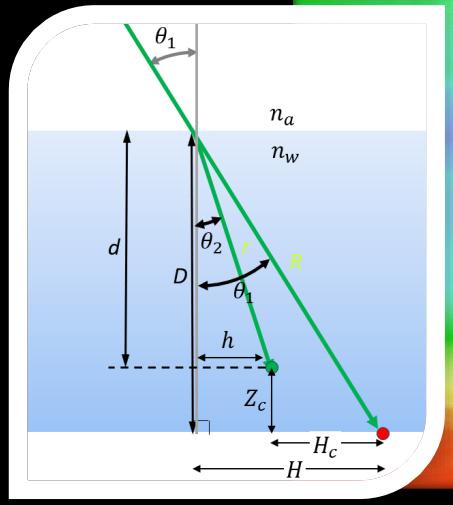
ATL24 Search Mask

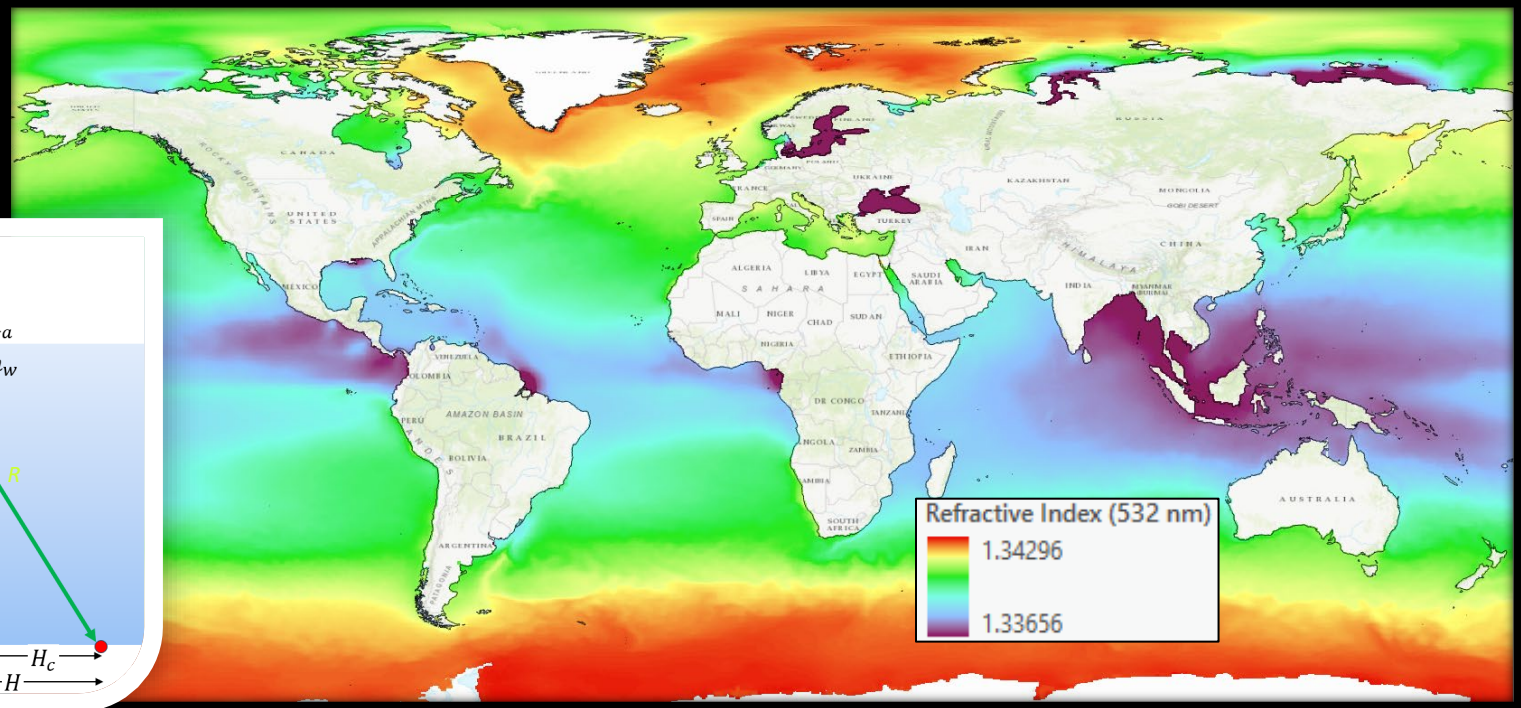
Dietrich, J., Reese A.R., Gibbons, A., Magruder, L., and Parrish, C. (2023) Analysis of ICESat-2 Data Acquisition Algorithm Enhancements to Improve Worldwide Bathymetric Coverage. *AGU Earth and Space Science,* Vol. 11 (2). https://doi.org/10.1029/2023EA003270



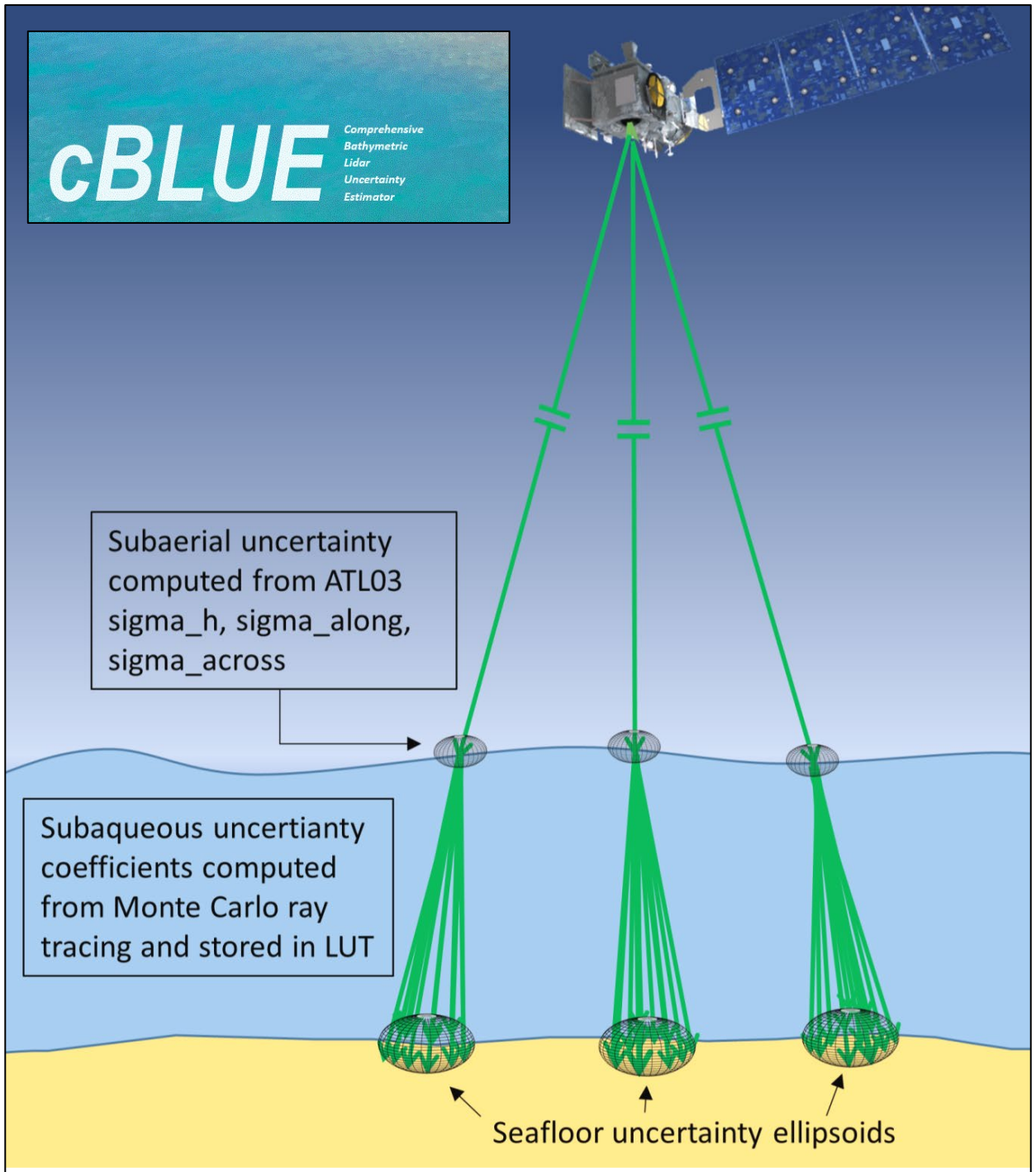
Global Refractive Index Layer

Dietrich, J.T., and C.E.Parrish, 2025. Development and Analysis of a Global Refractive Index of Water Data Layer for Spaceborne and Airborne Bathymetric Lidar. Earth and Space Science, 12(3).





ATL24 Total Propagated Uncertainty (TPU) Model



Algorithm 11 Uncertainty Algorithm

Input: K_d, wind speed, orthometric height (OH), pointing angle, sea surface height (SH), along track and across track uncertainty coefficients and offsets, ATL24 classification, and along-track (sigma_along), across-track (sigma_across), and vertical uncertainties (sigma_h) from ATL03

Output: THU, TVU

Depth = SH - OH

for $D_i \in Depth$ *and* $C_i \in Classification$ **do**

  if $D_i < 0$ *and* $C_i \; != 40$ **then**

    Vertical uncertainty coefficients and offsets $(A_v, B_v) \leftarrow K_d$, wind speed, pointing angle

    Horizontal uncertainty coefficients and offsets $(A_h, B_h) \leftarrow K_d$, wind speed, pointing angle

    Subaqueous vertical uncertainty $(SVU) \leftarrow A_v D_i + B_v$

    Subaqueous horizontal uncertainty $(SHU) \leftarrow A_h D_i + B_h$

    if $SVU < 0.10$ **then**

      $(SVU) \leftarrow 0.10$

    end if

  else

    $(SVU) \leftarrow 0$

    $(SHU) \leftarrow 0$

  end if

end for

$THU \leftarrow \sqrt{sigma\_along^2 + sigma\_across^2 + SHU^2}$

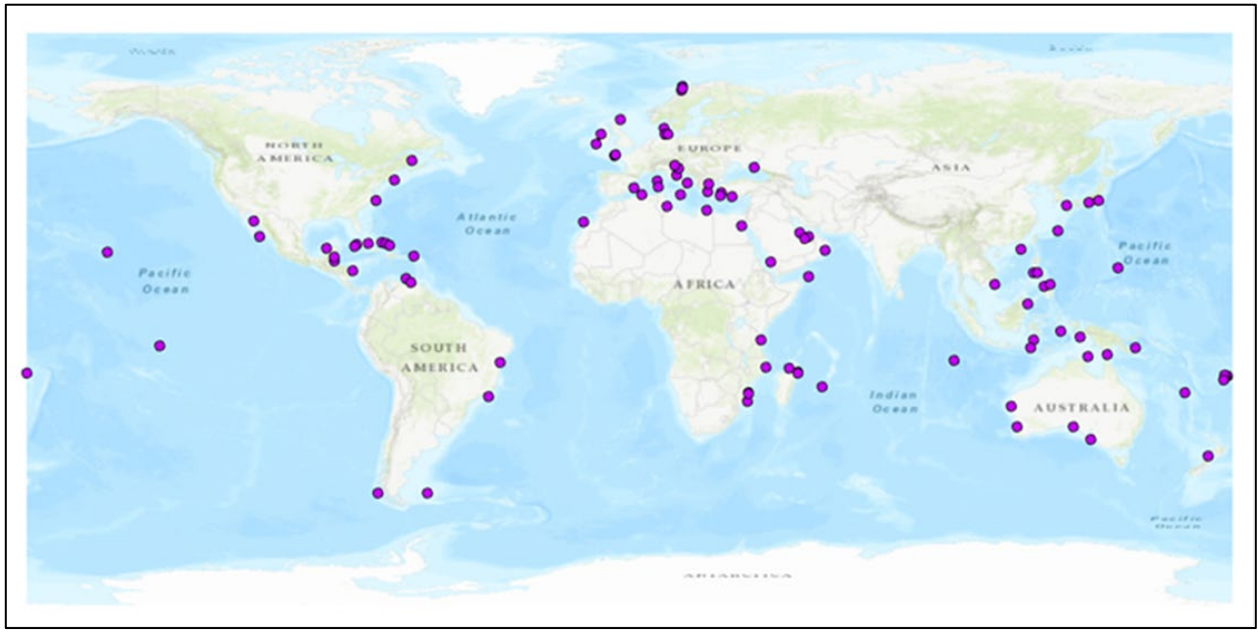
$TVU \leftarrow \sqrt{sigma\_h^2 + SVU^2}$

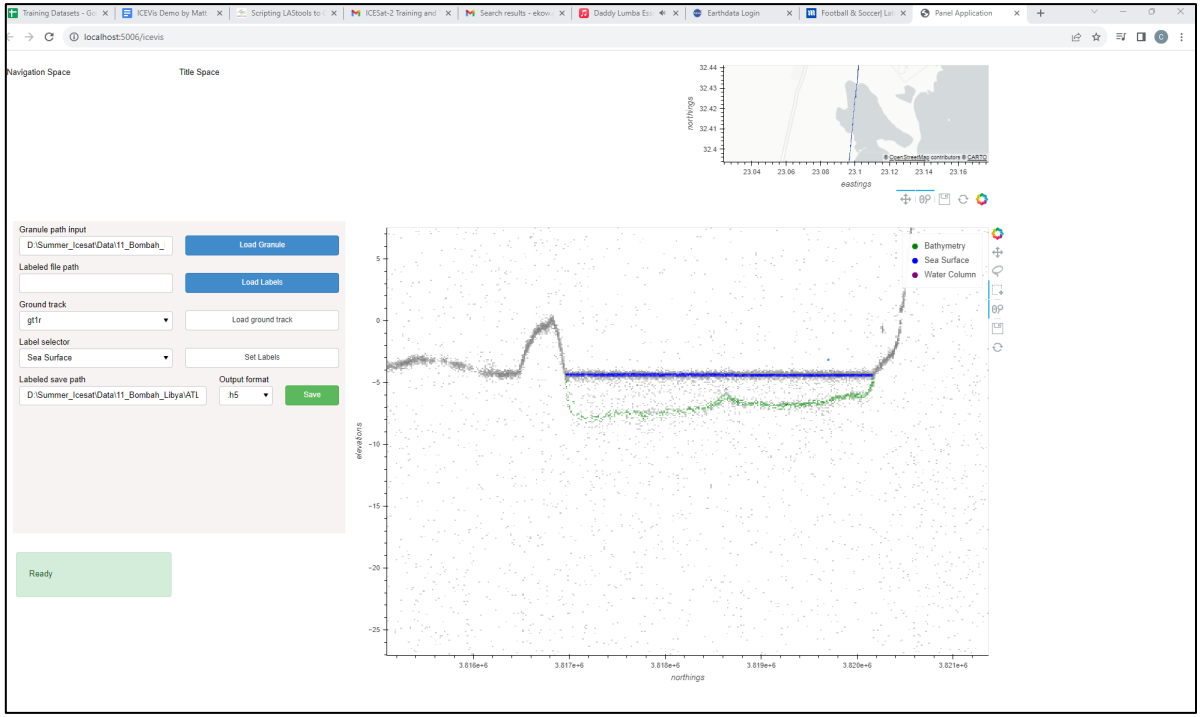
Eren, F., Jung, J., Parrish, C.E., Sarkozi-Forfinski, N. and Calder, B.R., 2019. Total vertical uncertainty (TVU) modeling for topo-bathymetric LIDAR systems. *Photogrammetric Engineering & Remote Sensing*, 85(8), pp.585-596.

Magruder, L., Parrish, C., Perry, J., Swinski, J.P, Holwill, M., Kief, K., and Corcoran, F. (2025). Ice, Cloud and Land Elevation Satellite (ICESat-2) Project Algorithm Theoretical Basis Document (ATBD) for Coastal and Along-track Bathymetry Product (ATL24). 1.0. NASA. doi: 10.5067/PXJMCZD0MYLN

Seafloor and Sea Surface Classification Training & Testing Database

- As part of ATL24 development efforts, we needed large training and testing database of ATL03 (geolocated photon clouds) data with sea surface and seafloor points accurately labeled
- Database of >150 sites developed by our team
- Wide variation in seafloor morphology and composition, substrate and cover types, and other environmental parameters



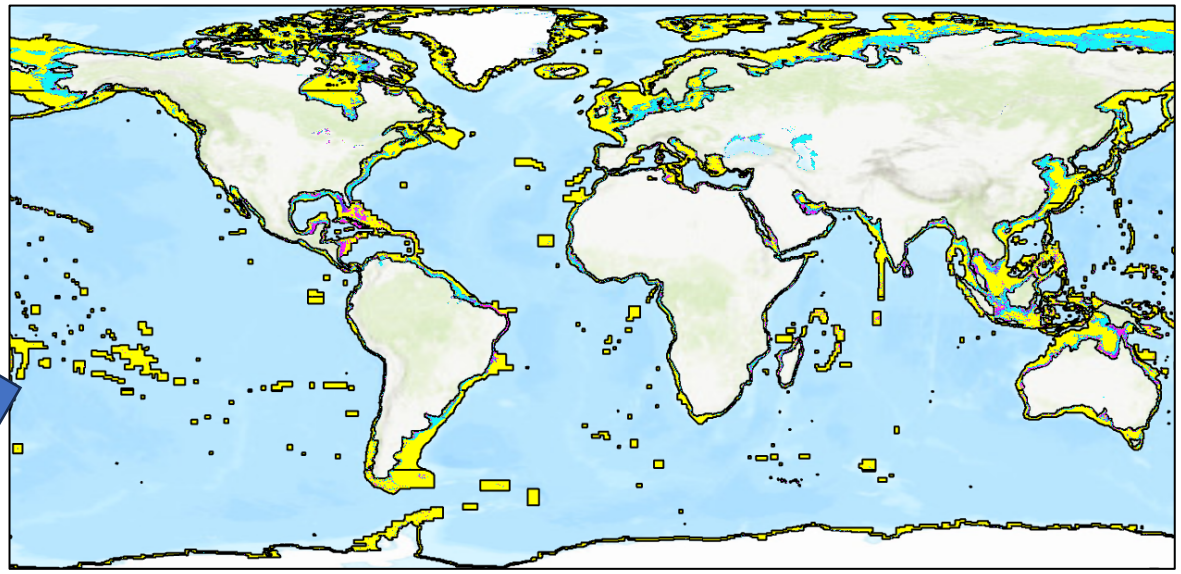


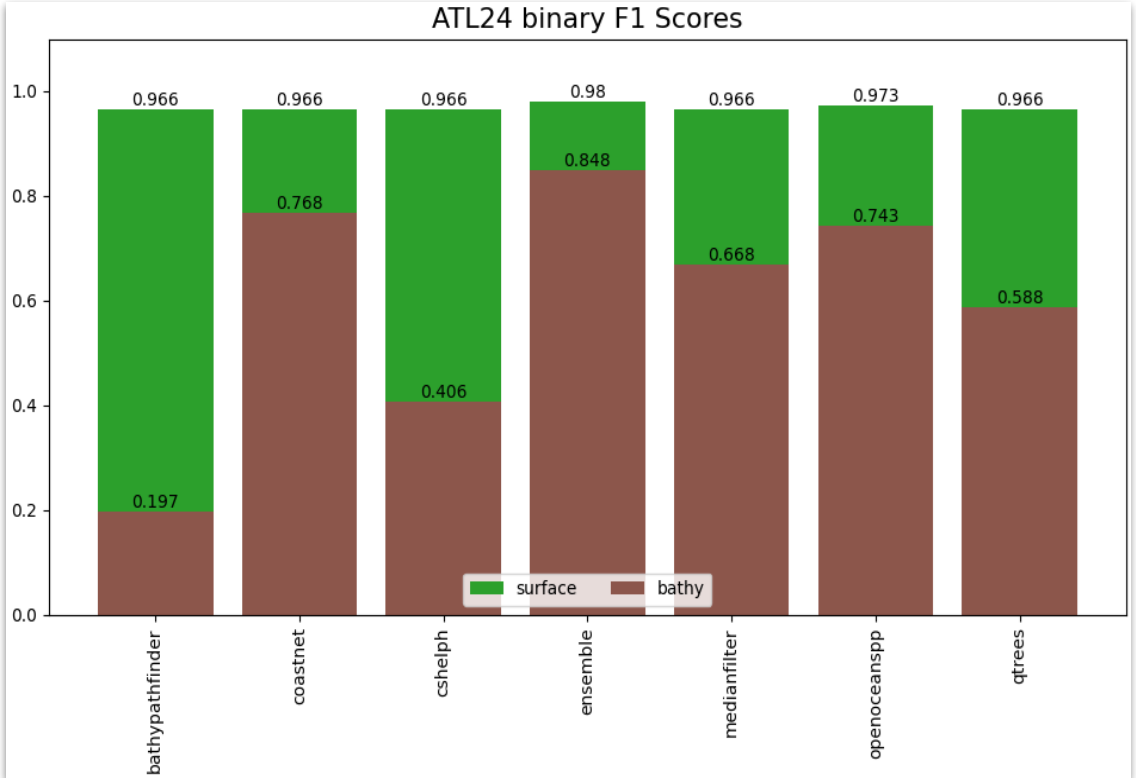
Disseminated via **ScholarsArchive@OSU**

DOI for the dataset:
https://doi.org/10.7267/j3860g66d
https://ir.library.oregonstate.edu/concern/datasets/j3860g66d

Ensemble ML model for seafloor and sea surface classification

- Auto-classification step is colossal undertaking
  - Needs to:
    - Work globally
      - Global range of seafloor morphologies, coast and water types, wind and wave conditions, etc.
    - Be fully automated
  - No single algorithm or model can provide good results everywhere
  - Solution
    - Ensemble ML
      - Leverages strengths of each base model/algorithm; **outperforms any individual classifier**
        - "Whole is greater than the sum of parts"
      - Another key benefit: provides a **classification confidence score**





L.A. Magruder, C. Parrish, J. Perry, M. Holwill, J.P. Swinski, and K. Kief, 2025. ICESat-2 coastal and nearshore bathymetry product algorithm development. *ESS Open Archive*.

Manually-labeled (reference)

Ensemble

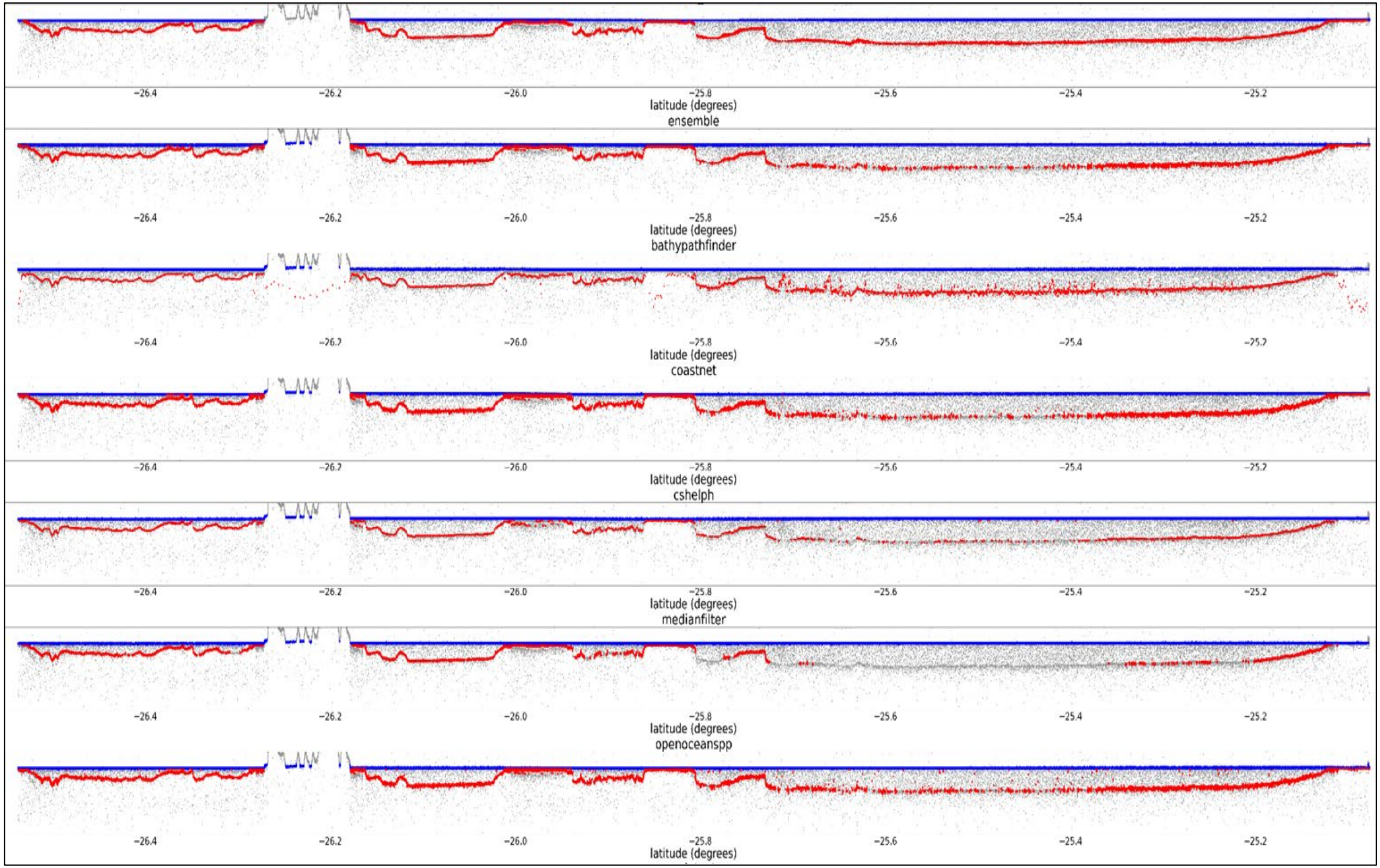
BathyPathfinder

C-SHELPh

CoastNet

Median filter

OpenOceans++

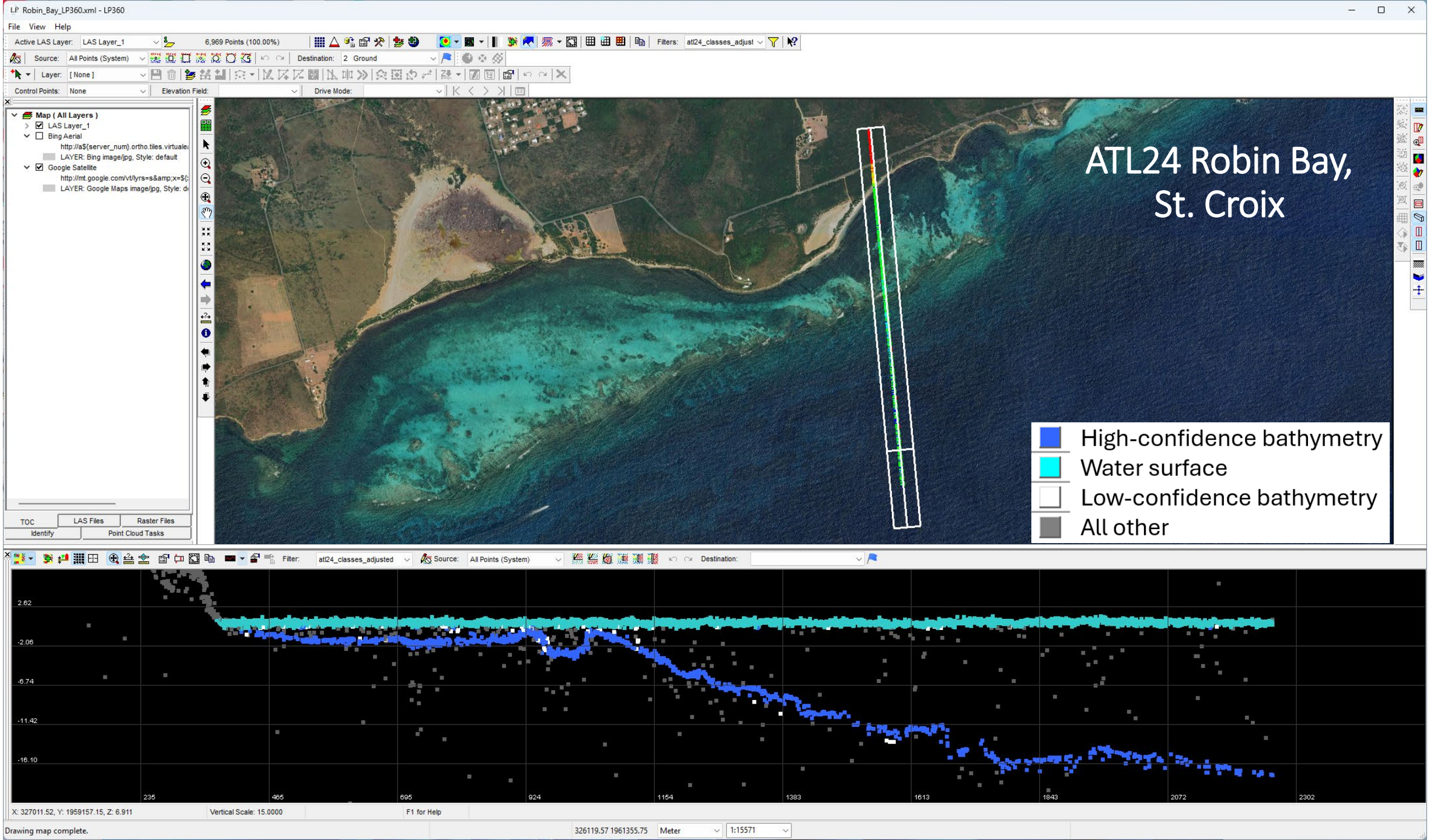


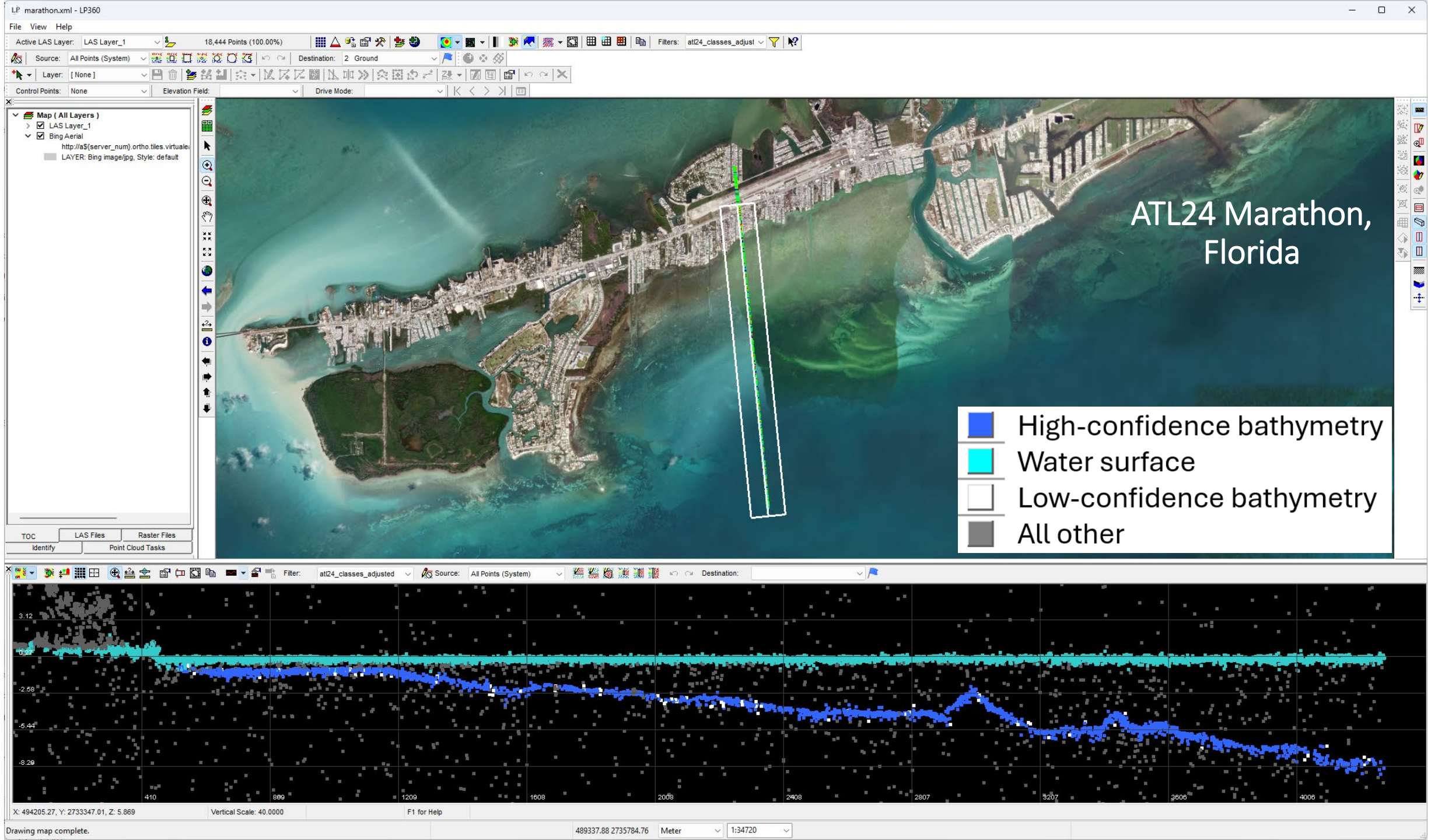
Stats from ATL24 Global Processing Run

Parameter	Value
Processing completion date	February 24, 2025
Processing time	13 days (AWS)
ATL24 data volume	27.6 TB
Total linear coverage of bathymetry	13.7 million km
Number of bathymetry (Class 40) photon returns	7.3 billion
Number of high-confidence bathymetry (Class 40) photon returns (confidence > 0.6)	4.7 billion

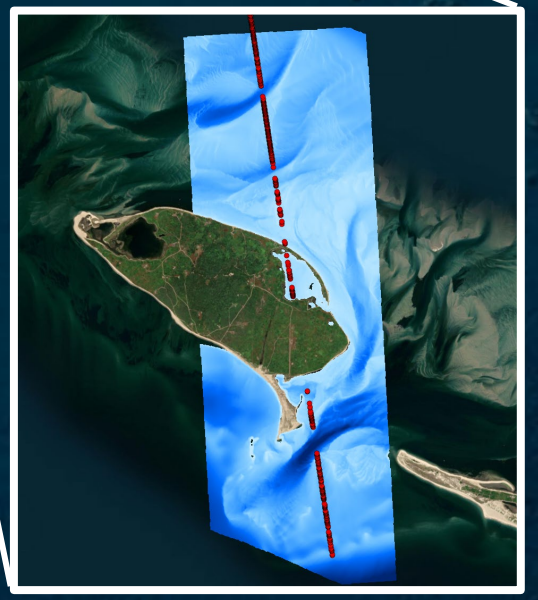
Parrish, C., L.A. Magruder, J. Perry, M. Holwill, J.P. Swinski, and K. Kief, 2025. Analysis and Accuracy Assessment of a New Global Nearshore ICESat-2 Bathymetric Dataset, ATL24. *ESS Open Archive*: https://essopenarchive.org/doi/full/10.22541/essoar.174388737.76018340/v1

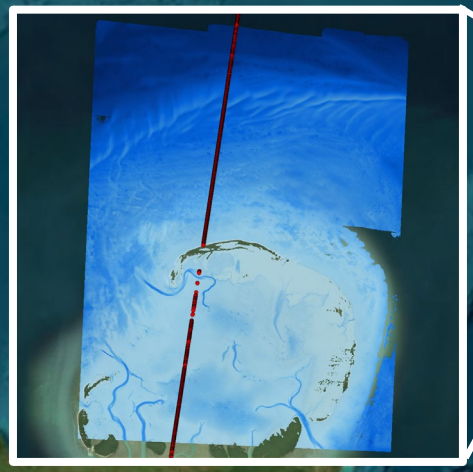
And many more…see paper


LP Robin_Bay_LP360.xml - LP360
File View Help
Active LAS Layer: LAS Layer_1
6,969 Points (100.00%)
Filters: atl24_classes_adjust
Source: All Points (System)
Destination: 2 Ground
Layer: [None]
Control Points: None
Elevation Field:
Drive Mode:
Map (All Layers)
LAS Layer_1
Bing Aerial
LAYER: Bing image/jpg, Style: default
Google Satellite
LAYER: Google Maps image/jpg, Style: d
TOC
LAS Files
Raster Files
Identify
Point Cloud Tasks
ATL24 Robin Bay,
St. Croix
High-confidence bathymetry
Water surface
Low-confidence bathymetry
All other
Filter: atl24_classes_adjusted
Source: All Points (System)
Destination:
2.62
-2.06
-6.74
-11.42
-16.10
235
465
695
924
1154
1383
1613
1843
2072
2302
X: 327011.52, Y: 1959157.15, Z: 6.911
Vertical Scale: 15.0000
F1 for Help
Drawing map complete.
326119.57 1961355.75
Meter
1:15571


marathon.xml - LP360
File View Help
Map (All Layers)
LAS Layer_1
Bing Aerial
TOC
LAS Files
Raster Files
Identify
Point Cloud Tasks
ATL24 Marathon, Florida
High-confidence bathymetry
Water surface
Low-confidence bathymetry
All other
3.12
-2.58
-5.44
-8.29
410
809
1209
1608
2008
2408
2807
3207
3606
4006
Drawing map complete.

ATL24 Accuracy Test Sites





Sandy Neck

Tuckernuck

Hatteras Inlet

Pensacola

Marquesas Keys

Marathon

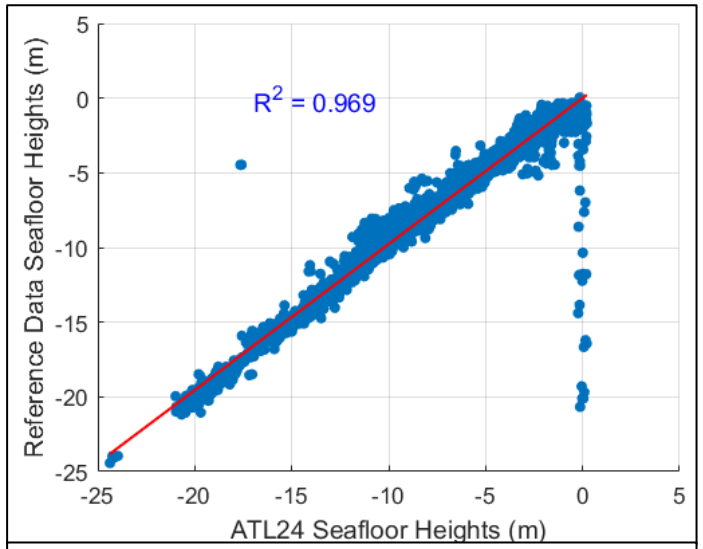
Mosquito Pier

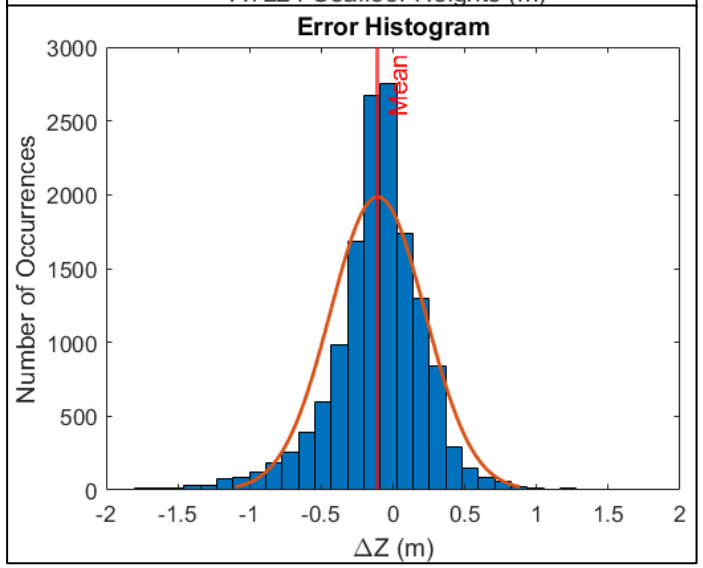
Robin Bay

Parrish, C., L.A. Magruder, J. Perry, M. Holwill, J.P. Swinski, and K. Kief, 2025. Analysis and Accuracy Assessment of a New Global Nearshore ICESat-2 Bathymetric Dataset, ATL24. *ESS Open Archive*: https://essopenarchive.org/doi/full/10.22541/essoar.174388737.76018340/v1

Accuracy Test Results

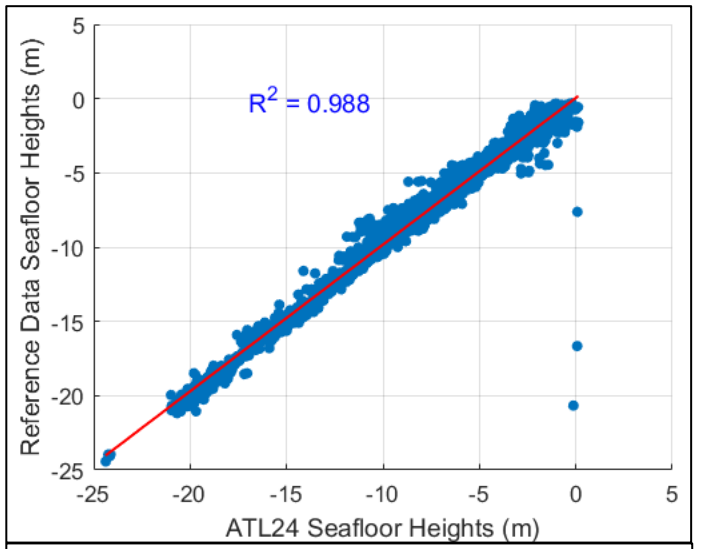
All Sites – All Bathymetric Points

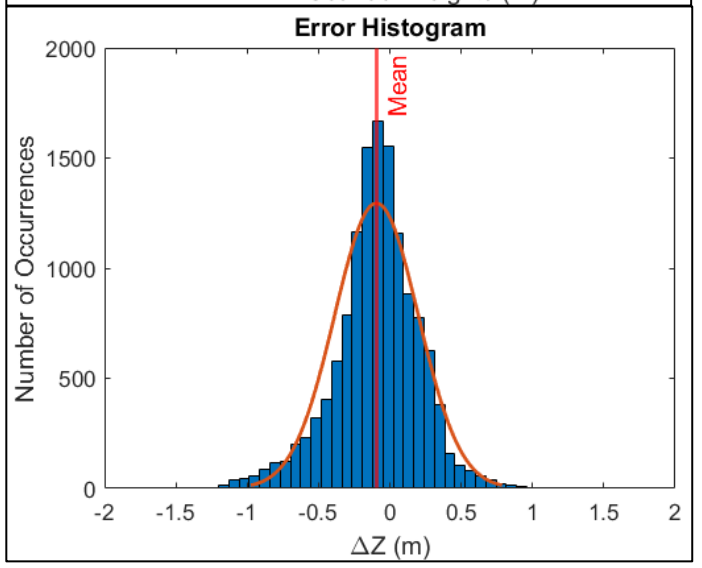




RMSE = 0.68 m
μ = -0.09 m
σ = 0.68 m
N = 14,555

All Sites – High-Confidence Bathymetric Points

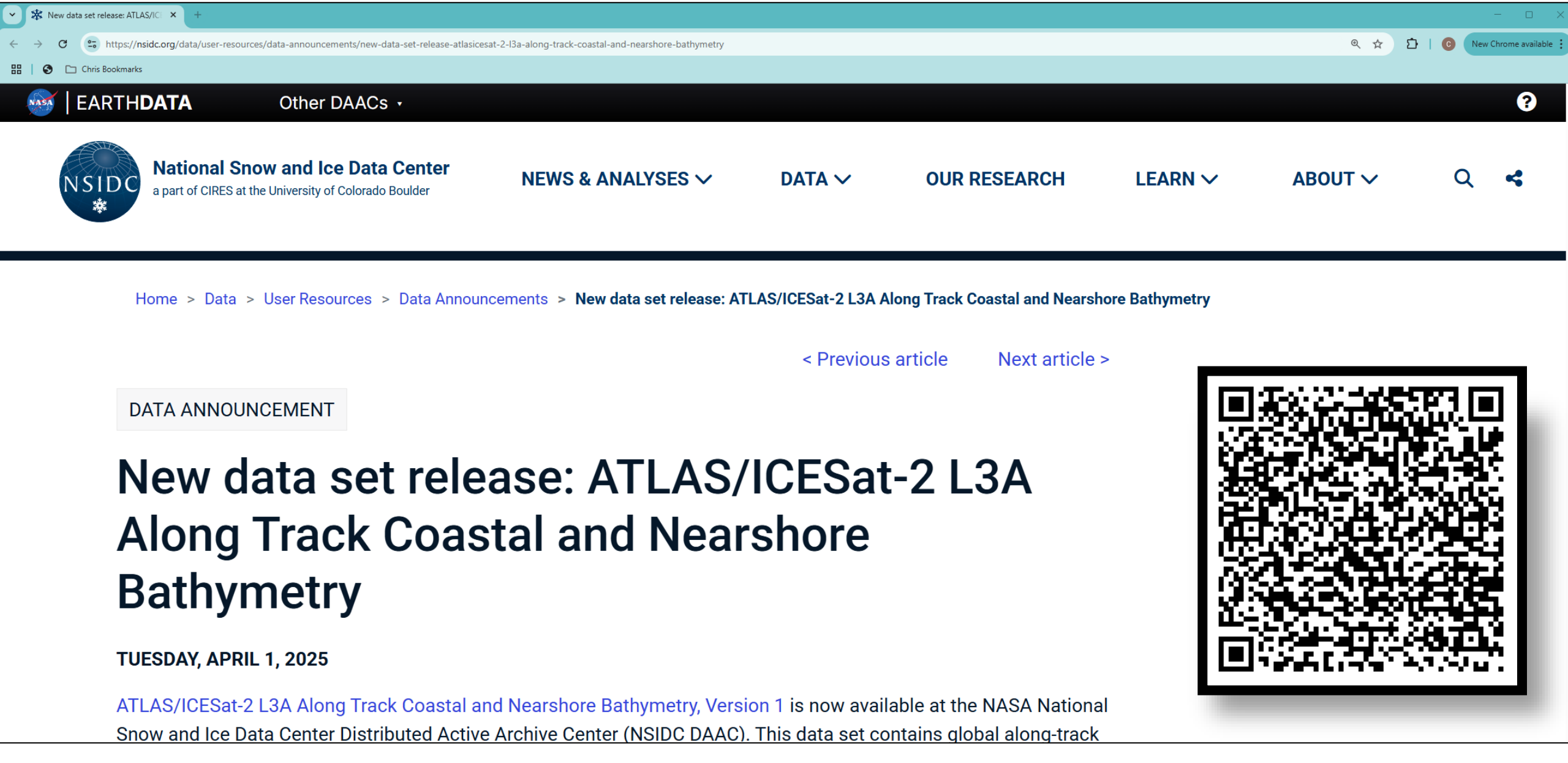




RMSE = 0.43 m
μ = -0.10 m
σ = 0.42 m
N = 13,419

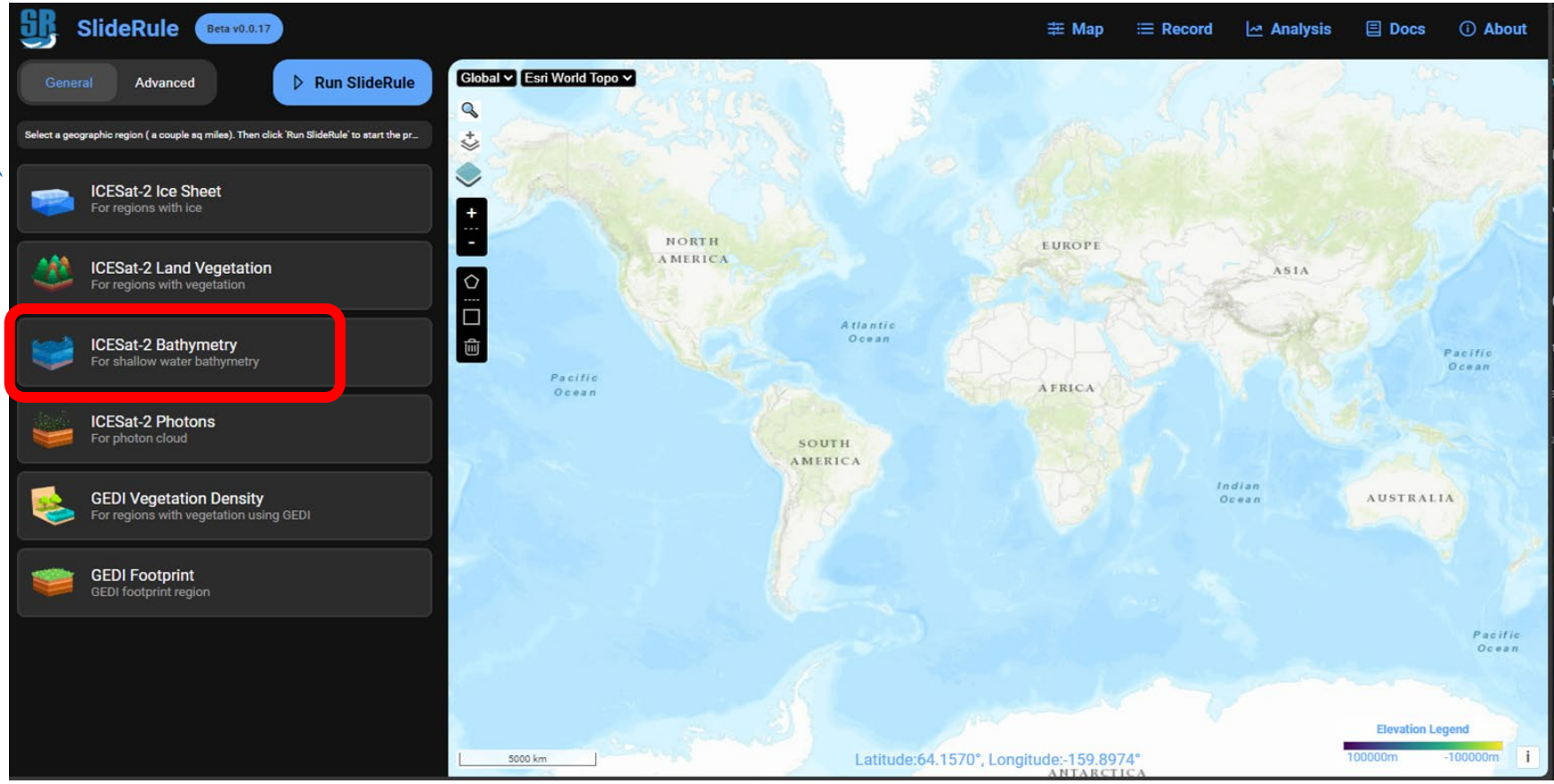
Parrish, C., L.A. Magruder, J. Perry, M. Holwill, J.P. Swinski, and K. Kief, 2025. Analysis and Accuracy Assessment of a New Global Nearshore ICESat-2 Bathymetric Dataset, ATL24. *ESS Open Archive*: https://essopenarchive.org/doi/full/10.22541/essoar.174388737.76018340/v1

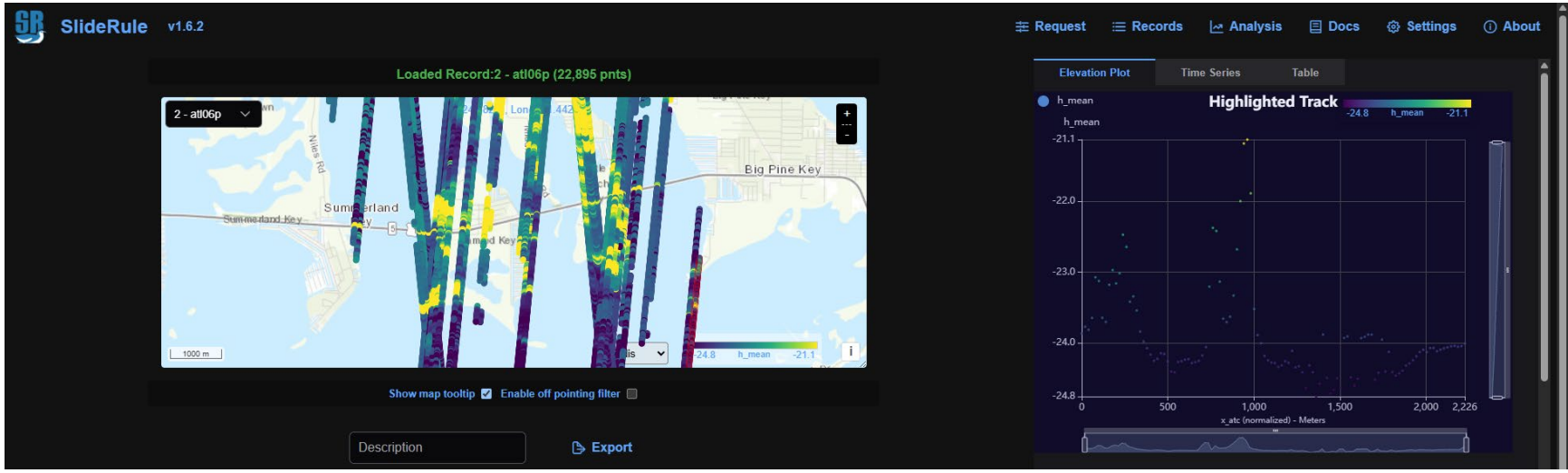
Accessing ATL24



Slide Rule Web Map Interface

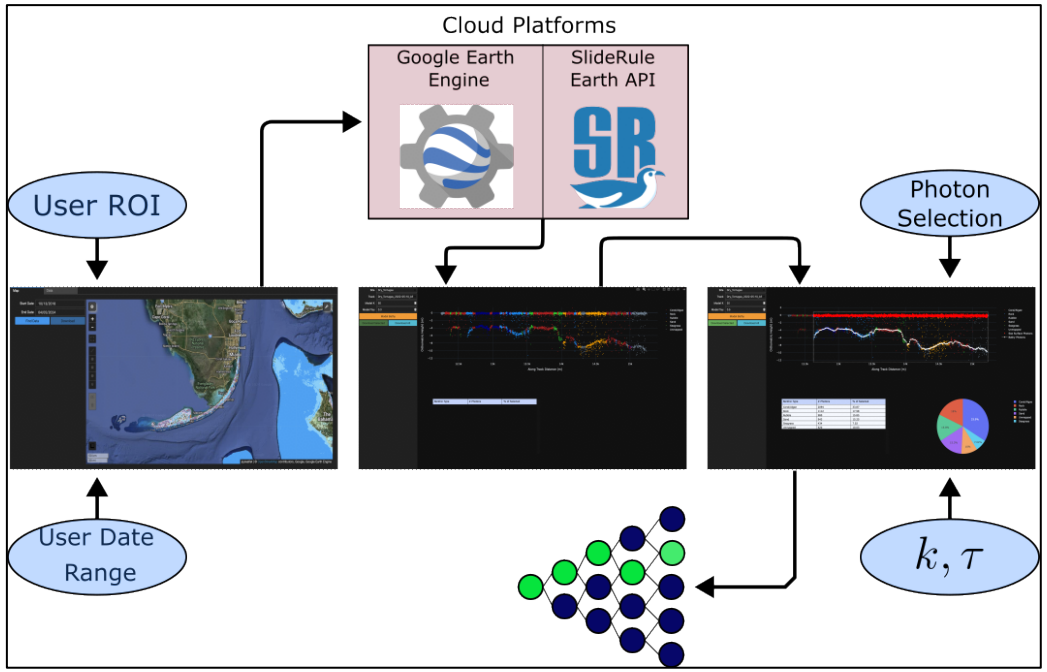
- Open-source API for on-demand processing of NASA science data in the cloud
- Will enable parameter customization based on use case
- Many output formats, including LAS and CSV





Ongoing and Future Work

- ATL24 Enhancements over time (future releases)
  - Periodically retrain base models and ensemble
  - Add additional algorithms/base models
  - Improve uncertainty model
  - Refine confidence values and thresholds
- Cloud based integration and processing of ICESat-2 bathymetry with other geospatial big data
  - Example (Forrest Corcoran research): add Sentinel-2 spectral reflectance values and Allan Coral Atlas attributes to ICESat-2 bathymetry
  - Train deep learning model for benthic habitat classification



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Thank you!

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