Supplement of Earth Surf. Dynam., 14, 291–311, 2026
https://doi.org/10.5194/esurf-14-291-2026-supplement

Supplement of

TerraceM-3: integrating machine learning and ICESat-2 altimetry to estimate deformation rates from wave-abrasion terraces

Julius Jara-Muñoz et al.

Correspondence to: Julius Jara-Muñoz (jara@hochschule-bc.de)

S1 TERRACEM Pre_MAP, instructions

S1.1: To start TerraceM_Premap simply go to the TerraceM_Premap directory in MATLAB® and write in the command window TerraceM_PreMAP.

S1.2: Set the directories that include the path to TerraceM_MAP and the path to topotoolbox.

S1.3: load the topography in .tif format and UTM coordinates and the risers which are polylines in shapefile format (.shp) created in QGIS with the same coordinate system as the topography. The risers should include a numeric attribute called level (short integer).

Figure S1: Pre_MAP input directories

S1.4: Proceed to swath extraction. Define a swath width, for instance for the example data at Cerro El Huevo the swath width is around 3000 m. Sampling is usually calculated by default based on the raster resolution. Smoothratio is usually 0.

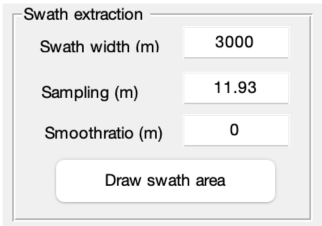

Figure S2: Pre_MAP Swath parameters

S1.5: When the parameters are set, press draw swath area, this will display the topography and risers into a single map view. Mark two points that defines the start and end of the swath profile. The swath should be oriented parallel to the trace of the inner edges.

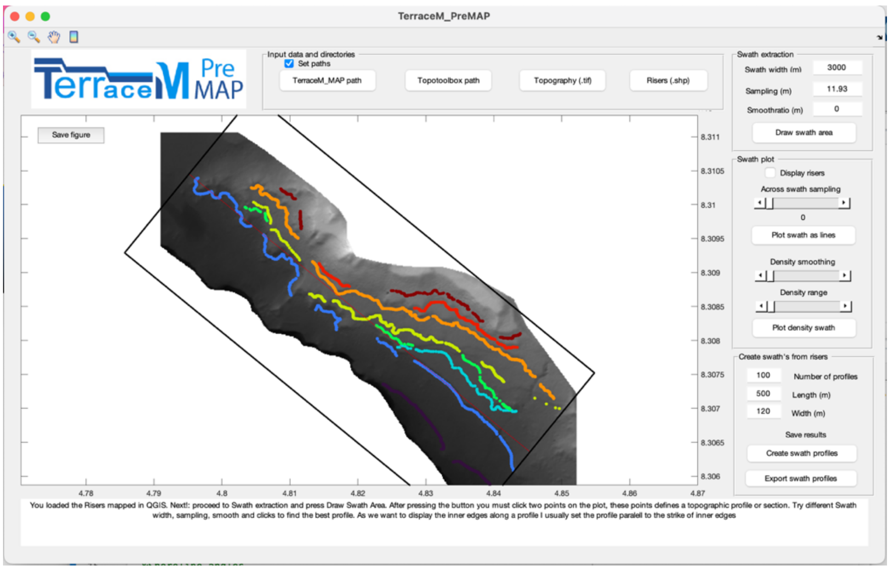

Figure S3: Pre_MAP display

S1.6: If you are satisfied with the swath area proceed to the Swath plot section. It is recommended go directly to the button "plot swath as lines" using the default across swath sampling value. Afterwards you can vary these values to improve visualization.

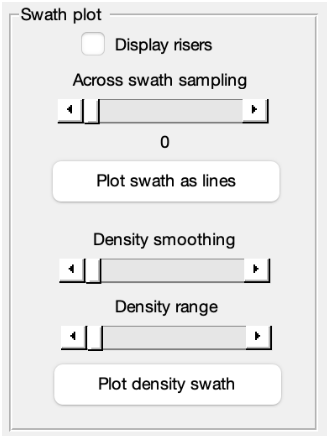

Figure S4: Pre_MAP superswath parameters

After pressing this button, the stacked swath profile will be displayed. You can add the riser by activating the tick button and pressing Plot swaths as lines again. Use this visualization to check if the risers were well mapped. If you find errors, you can edit the risers shapefile in QGIS and load them again. Repeat this procedure until the riser are well mapped.

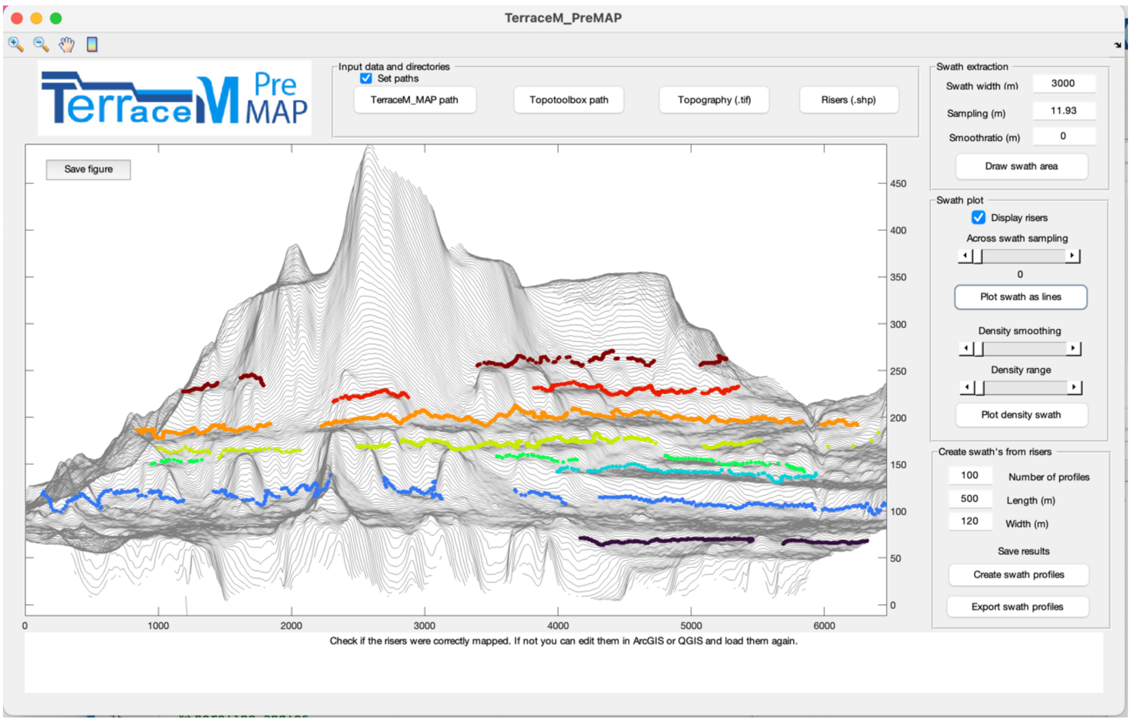

Figure S5: Pre_MAP superswath display

S1.7 (optional): Change to plot desnity swath by pressing the corresponding button, adjust density smoothing and density range to improve the visualization. Use this to check if your risers are well mapped. You can edit the risers in QGIS and reload them until they are well refined. When ready proceed to the next panel.

S1.8: Once the risers are corrected and refined you can extract perpendicular swath profiles. Define the number of profiles to extract, the length of the profiles and their width. The length should encompass a single terrace level so you will need to check the mean width of the terrace treads. This does not need to be so accurate, but preferably each profile should include a single terrace level to map. The profile width should not be less than 10 to 20 times the pixel size of the topography to avoid artifacts.

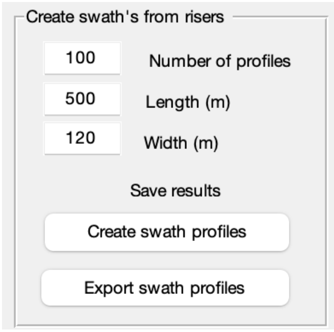

Figure S6: Pre_MAP swath creation parameters

S1.9: when the parameters are ready press Create swath profiles. If you are satisfied with the result press export swath profiles. Otherwise change the parameters until you get the desired result. The swath profiles are exported as a polygon shapefile in the same folder as the topography dataset and can be used to map marine terraces in TerraceM MAP.

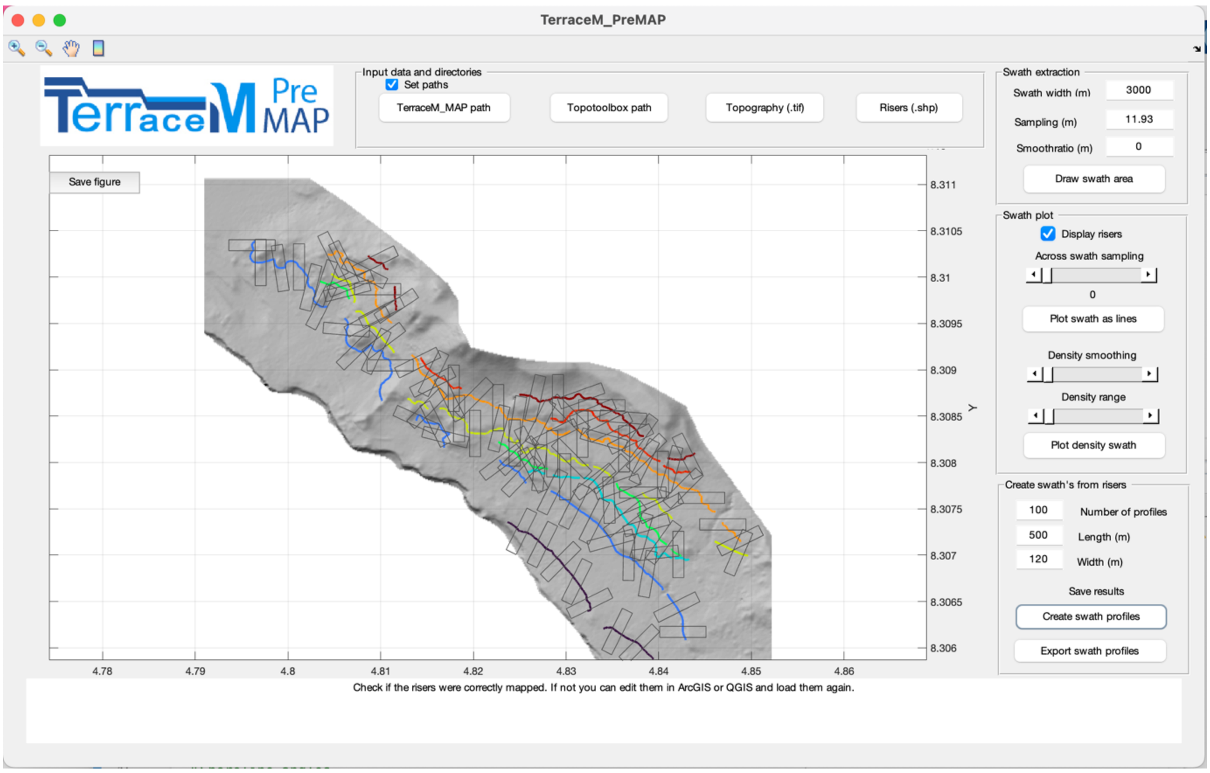

Figure S7: Pre_MAP swath boxes display

S2. Neural Network setup

The TerraceM ML mapping uses two independent NN (neural networks), one for mapping the paleo-platform and one for mapping the paleocliff of the marine terrace morphology. Each NN consisted of three hidden layers with 100 neurons per layer and used a log-sigmoid activation function. The activation function compresses an infinite input range into a finite output range, which enables non-linear learning. However, as inputs become large, the derivative of the log-sigmoid function can approach zero, this can obscure the estimation of weights and bias and conceal the NN training. The gradient (or derivative) shows how much the output error changes with respect to each weight and bias. It tells the direction to adjust them in order to reduce the error, so the model can make better predictions. If the derivative becomes too small then the NN learning becomes slow and the training behaves unstably or simply stop. To address this issue, we used the Resilient Backpropagation (Rprop) training algorithm. Unlike traditional gradient-based methods, Rprop updates weights and biases based only on the sign of the gradient rather than its magnitude. This allows each weight to be adjusted independently using a fixed update factor, improving training stability and processing time. As a result, the NN can learn complex non-linear relationships more reliably. Weights and biases are initialized using the Nguyen-Widrow (initnw) method, which evenly distributes values across neurons to ensure a smooth training process.

The NN training begins by loading a dataset containing the swath profiles, from which the x-z elevation pairs are extracted and rescaled to a 0-1 range to ensure comparability among profiles. Each swath is checked for orientation and corrected if necessary, and its spatial and vertical ranges are recorded for later normalization. Cliff and platform segments, based on manual mapping, are then interpolated to uniform lengths, rescaled within the same coordinate bounds, and stored as target datasets, while the full swath profiles are defined as input data. The neural networks are then trained for 1,000 epochs with a low learning rate (0.0001) to ensure stable convergence, and using the entire training dataset (1000 swath profiles) in each epoch. Once trained, both networks are saved for later integration into the TerraceM–3 workflow, where they enable automated recognition of terrace morphological features from ICESat-2 elevation profiles.

During the NN's application, the predictions are refined to accurately delineate the terrace morphology along each swath profile. For each profile, it identifies the maximum and minimum predicted elevation values and determines their intersections with the original swath to locate the upper and lower boundaries of both cliffs and platforms. Small vertical offsets are iteratively tested to account for local variability and ensure stable shoreline angle detection. The code includes logical conditions to resolve ambiguous cases such as multiple or missing intersections, inverted geometries, or overlapping features by selecting the most geomorphologically consistent points. These corrected coordinates define the top and base of cliffs and platforms, which are then extrapolated and intersected to define the position of the shoreline angle.

S3. TerraceM ICEsat-2

The ICEsat-2 satellite carries the key instrument ATLAS, designed to measure surface elevation with high precision by emitting laser pulses toward Earth's surface and recording the time it takes for the photons to return. To enhance sensitivity compared to traditional LiDAR, ATLAS employs a photon-counting approach, detecting individual photons reflected from the surface. The instrument emits green laser pulses (532 nm) at a rate of 10 kHz, which are split into six beams arranged in three pairs to improve spatial coverage. These beams include both strong and weak energy levels, allowing for differential penetration in ice while maintaining high performance over land. By precisely timing photon travel and applying corrections for atmospheric and geolocation factors, ICESat-2 achieves centimetre-level elevation accuracy. Additionally, like traditional LiDAR, ATLAS data can be processed to classify and filter photon returns, enabling the extraction of bare-earth topographic profiles (Abdalati et al., 2010; Field et al., 2020; Jasinski et al., 2021; Markus et al., 2017; Khalsa et al., 2022).

The outputs of ATLAS data are organized into several standard data products, each specialized for different surface types and stored as .h5 files. ATL03 provides geolocated photon data, serving as the foundation for higher-level products (Neumann et al., 2023). ATL08 provides canopy and vegetation structure (Neuenschwander et al., 2023), making it valuable for environmental and forestry applications (Neuenschwander and Pitts, 2019). Each data product contains a structure arranged by beam and beam level. TerraceM ICEsat combines all beams and filter them by weak and strong levels. Usually, strong profiles have the higher number of photons, including weak beams can be useful if strong profiles are scarce.

TerraceM ICEsat can download ATL06 (Smith et al., 2023) the doublet ATL03 - ATL08 data products. ATL03 and ATL08 are combined to obtain a bare earth profile based on the "photon Id" (Markus et al., 2017; Neuenschwander and Pitts, 2019). This feature is contained in both data structures and allows to link the geolocation data of ATL03 for each photon with their corresponding classification in ATL08. The photon classification includes: ground, canopy, upper canopy, noise and unclassified (Neuenschwander and Pitts, 2019). By filtering out all except the ground, we obtain a bare-earth photon profile, which is then used to map the marine terraces using the GUI TerraceM_ICESat_MAP.

To download the ICESat-2 data TerraceM_ICESat connect with the Harmony servers of NASA using PyHarmony library, which provides a direct interface to the Earthdata system. The script initializes a Harmony client using the user's Earthdata credentials and constructs a data request based on a defined ICESat-2 collection ID, spatial bounding box, and temporal range. These parameters are passed as command-line arguments, typically from MATLAB, to ensure full automation within the TerraceM–3 workflow. Once the request is configured, the script submits it to the Harmony service, which processes the subsetting operation on NASA's servers and returns a unique job identifier (Job ID). This Job ID is stored locally to allow monitoring and retrieval of results. A second script is used to check the job status, if the job has completed successfully, the script retrieves and lists the result URLs corresponding to the processed ICESat-2 granules, allowing the user to access or download the data. It also provides diagnostic information, including the number of returned granules and job metadata. A third python script is then used to download the data after job completion. The files are downloaded into a specified local directory, ensuring existing files are overwritten to maintain synchronization. Detailed progress and error information are recorded through a logging system for traceability.

Finally, the data are converted into the TerraceM format, retaining only the essential attributes from each ICESat-2 product, and stored as .mat files corresponding to the ATL03, ATL08, or ATL06 datasets. The laser beams in these files are then filtered according to signal strength, photon count, and photon confidence level to extract single-photon elevation profiles, which are subsequently saved in .mat format for further processing.

S4 TERRACEM ICESat, instructions

S4.1: Installation of TerraceM ICESat

S4.1.1: Install Matlab with mapping toolbox and Anaconda (python). Follow the installation instruction for your OS (Windows, Mac, Linux)

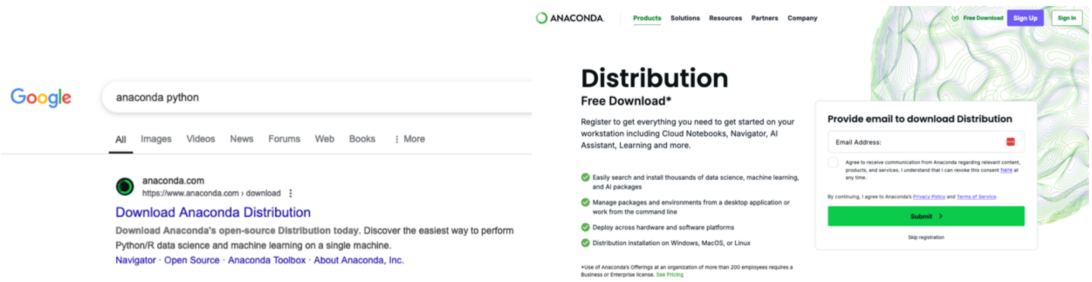

Figure S8: Search and download Python Anaconda distribution. © Google LLC. Used for illustrative purposes only. © Anaconda, Inc. Anaconda® is a trademark of Anaconda, Inc. Used for illustrative purposes.

S4.1.2: Check which version of Python is installed. Within Matlab write pyenv in the command window. Version id the version of Python installed and linked with Matlab. Any version of Python should work, we recommend a version higher than 3.2.

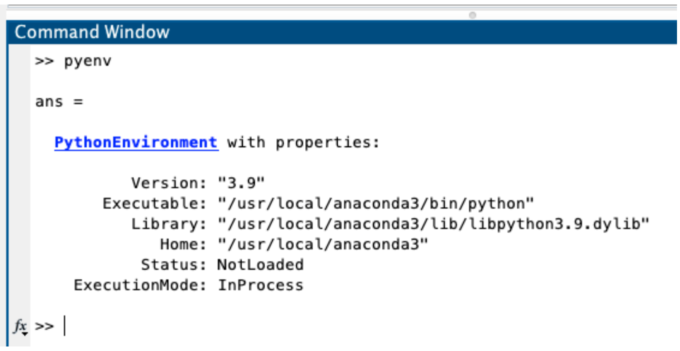

Figure S9: Matlab® command window. © The MathWorks, Inc. MATLAB® is a registered trademark of The MathWorks, Inc. Used for illustrative purposes.

S4.1.3: Before using TerraceM ICESat-Process create an account in Earthdata from NASA

a) go to https://urs.earthdata.nasa.gov/users/new and register

b) go to your account in earth data login https://urs.earthdata.nasa.gov/home

c) You must approve the EULA's: go to the menu EULAs and agree all of them to avoid any conflict with servers

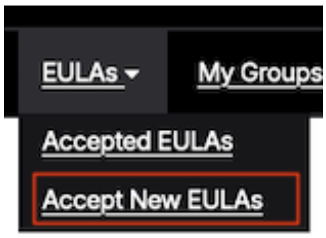

Figure S10: Screenshot of the NASA Earthdata webpage (earthdata.nasa.gov).

Courtesy of NASA. NASA/Earthdata. Public domain.

S4.1.4: Before running Matlab/Python Run Call_python.py to check the path to your python installed directory, this is a requirement

You can use the editor "sublime" to run python scripts. It can be downloaded free for Mac, Windows, or Linux:

https://www.sublimetext.com/

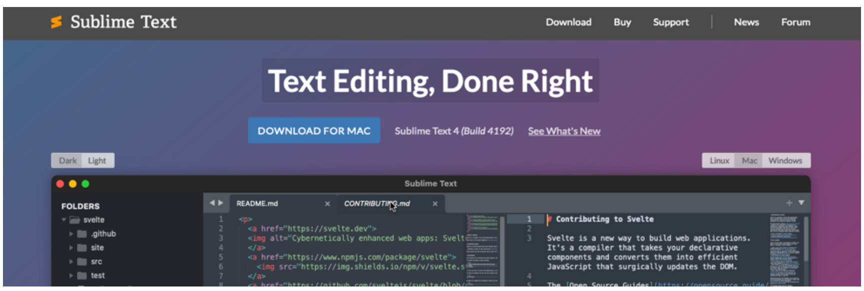

Figure S11: © Sublime HQ Pty Ltd. Sublime Text® is a registered trademark of Sublime HQ Pty Ltd. Used for illustrative purposes.

Search for Call_python.py within files in the folder of TerraceM IceSat Map. Open it with the text editor (Sublime).

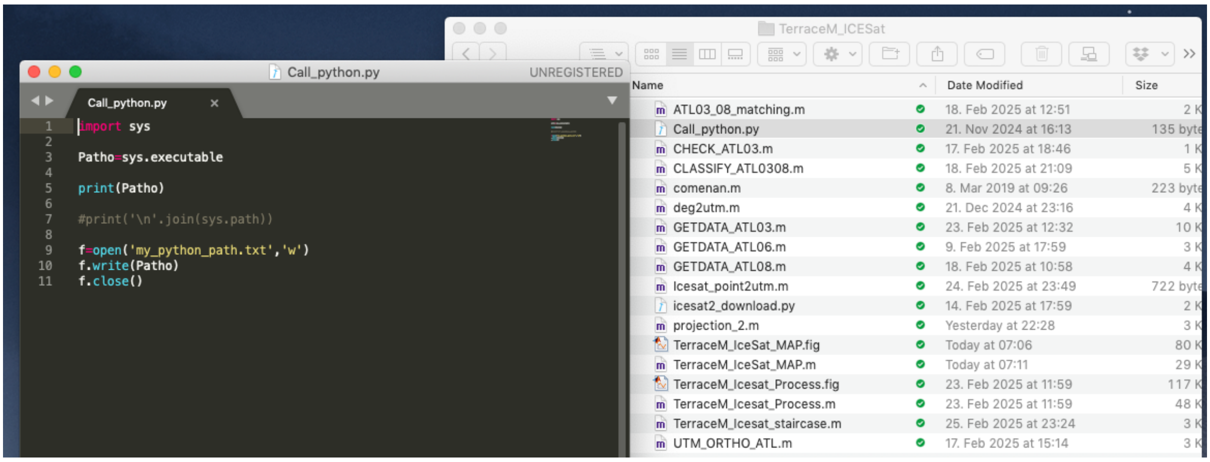

Figure S12: Running call to python script. © Sublime HQ Pty Ltd.

In the menu ribbon of Sublime go to Tools, and then Build. This will create a .txt file with the path to Python inside the TerraceM_IceSat_MAP folder. Afterwards you can close the python script.

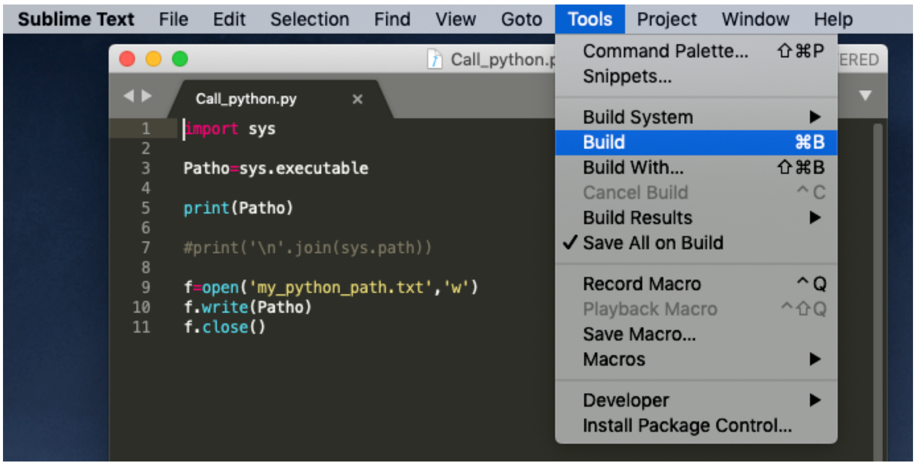

Figure S13: Running call to python script. © Sublime HQ Pty Ltd.

create a new document in sublime and paste this code, then press again build. This can also be done in the console, copy and paste the code below. This code installs python libraries necessary for TerraceM_ICESat to run properly.

```
pip install harmony-py

Pip install numpy

Pip install h5py
```

S4.2: Running TerraceM_Icesat_Process

S4.2.1: Inside Matlab, got to the folder TerraceM_ICESat Map. Use the navigation bar at the top of the Matlab interface to navigate to this folder. Should be located inside the main TerraceM-3 folder.

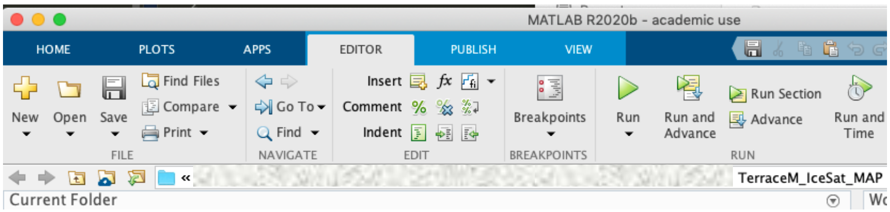

Figure S14: Go to directory in Matlab®. © The MathWorks, Inc. MATLAB® is a registered trademark of The MathWorks, Inc. Used for illustrative purposes.

Type TerraceM_Icesat_Process in the command window

Inside TerraceM_Icesat_Process. The GUI interface follows a workflow from left to right and from top to bottom. You can also jump over this workflow and go directly to specific modules like module 3, for loading .h5 data downloaded in previous sessions. Or loading previously processed data.

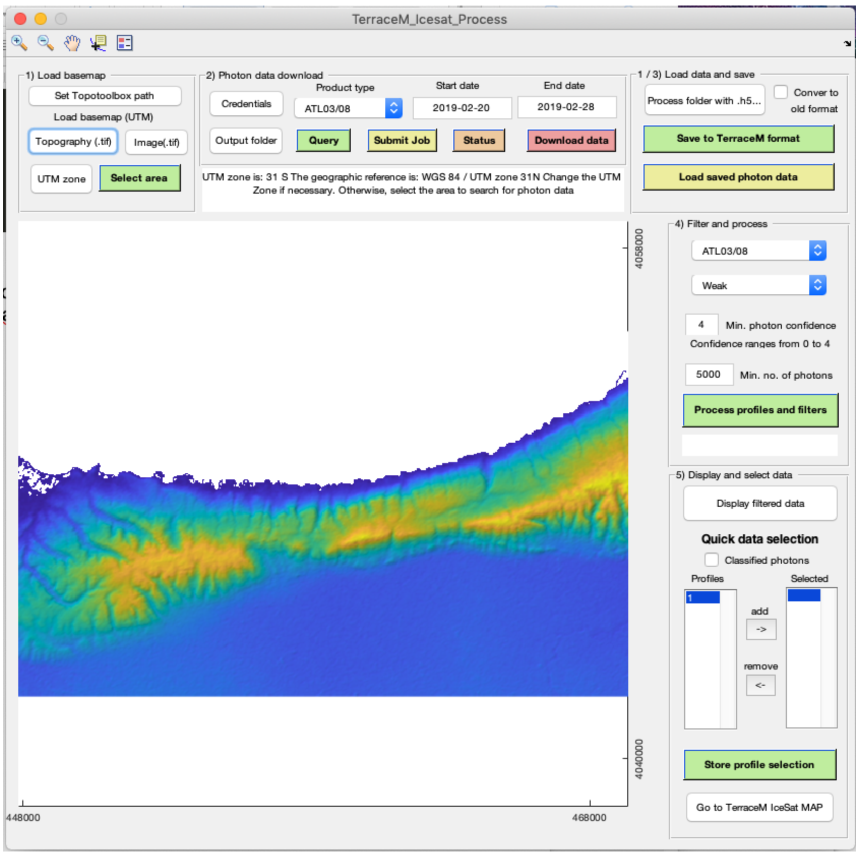

Figure S15: TerraceM ICESat Process interface

S4.2.2: The first Module is for setting the directories and loading the topography used as basemap. The path to topotoolbox is necessary for loading the topography and satellite images. You will find the topotoolbox folder inside the folder TerraceM-3. The topography or satellite image should use a projected coordinate reference system e.g. WGS84 + UTM + zone and in .tif format, the UTM zone would load automatically. The UTM zone button can be used alternative if the user wants to change the UTM zone of the data. Loading a topography or satellite image is a requirement for selecting the photon area for data download (Select area button).

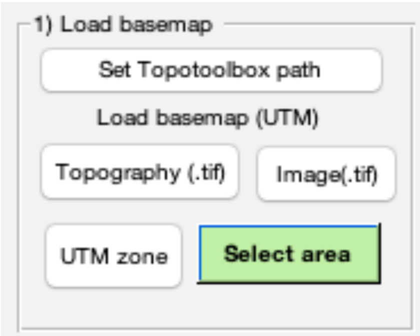

Figure S16: TerraceM ICESat Process load basemap parameters

S4.2.3: The second module is designed to select the IceSat-2 product, the time interval of data parameters and download the data.

a) First set you credential for earthdata log in (See instructions in Chapter 1, Step 3 to create an account).

b) Then define the output folder for the ICESat-2 data.

c) ATL03/08 product types are recommended because of the highest resolution and the possibility to filter out vegetation. ATL06 can be used together with ATL08/03 for shallow bathymetry extraction.

d) Define the time interval, the dates of the datasets range since April 2018 to the present. Consider that the longer the time interval and area the higher the volume of data downloaded.

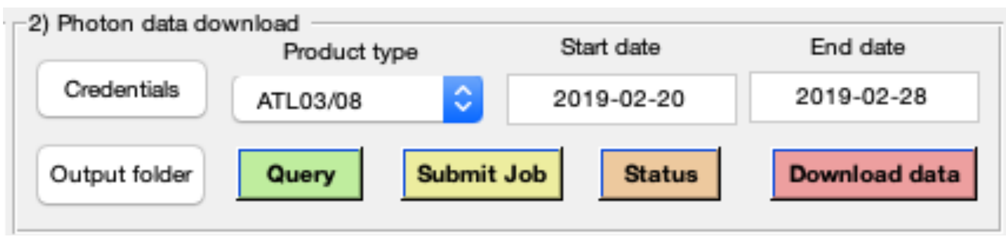

Figure S17: TerraceM ICESat Process set query/download parameters

e) When product type and dates are ready press the green button "query", this will connect Terrace_ICESat_Process with the Harmony server of the NASA. The Query status will be displayed in the information window below the module 2. You will see the number of granules (files) to download and the size in megabytes (This size is approximate and estimated from raw granules, usually the final data downloaded is a bit lighter).

f) If you are satisfied with the query then press the yellow button "Submit Job". This will connect again with the Harmony server and will send the data request. The Harmony server will then process and subset the data to the area specified, this is a process that can take minutes to hours depending of the data size. After submitting the job, you can even close TerraceM_ICESat_Process if necessary and check later. The Harmony server will ocntinue processing the request in the cloud. Be careful not submitting too many jobs at the same time to avoid server overload and account problems.

g) To check if the data is ready for download press the orange "Status" button. This will connect TerraceM_ICESat_Process with Harmony. The status will be displayed in the information window below the module 2.

h) if the Status message if "Successful" then press the red button "Download Data", the Icesat-2 .h5 files will start downloading in the selected output folder. This can take some time depending of your internet connection and the size of the dataset downloaded.

S4.2.4: The third module is designed to convert ICESat-2 data to TerraceM format (Matlab®) or load previously converted files.

a) After all the files have downloaded press the grey button "Process folder with .h5 files" Then navidate to the folder where the .h5 ICESat-2 files were downloaded. For a matter of compatibility, it is convenient to activate the tick button "Convert to old format" this ensures compatibility with older versions of Matlab® and newer ones. A new folder named "reformat" is created inside the folder containing the original .h5 files, the original .h5 files will be deleted to save space. Activating the conversion would not be necessary for Matlab® versions newer than 2026.

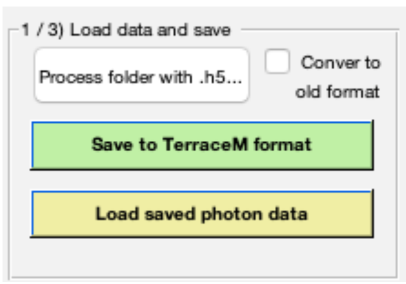

Figure S18: TerraceM ICESat Process, process and store downloaded .h5 files

b) After the files are converted you can save the results by pressing the green button “Save to TerraceM format. Select the directory where to save the files, usually together with the .h5 files. In case you are using ATL03/ATL08 data two files will be created.

c) If you converted your .h5 files to TerraceM format before, avoid the steps a and b and simply press the yellow button “Load saved photon data”. I you want to load ATL03/ATL08 data then select both .mat files (ATL08_xxx.mat and ATL03_xxx.mat). This step is not necessary if you are processing the .h5 files for first time.

S4.2.5: This module allows filtering and processing the ICESat-2 data converted to TerraceM format and creating a profiles .mat file.

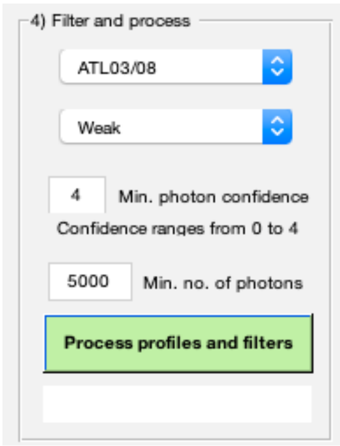

Figure S19: TerraceM ICESat Process, filter option for profile creation

a) First select the type of dataset.

b) Then select the signal strength, weak, strong or weak/strong. We suggest using weak/strong in order to see as many profiles as possible. Both, weak and strong signals are very accurate and can be used without inconvenience when working either with bathymetry or topography.

c) Select the minimum photon confidence. The confidence ranges from 0 to 4 where 4 is the highest confidence. For working with topography we suggest using values 3 or 4, if you want to extract bathymetry you can use values staring from 1 in order to get more photons crossing through the water.

d) Select the minimum number of photons per profile. Depending of the length of the profiles this number can vary, we recommend staring with a low values, e.g. 500 and then increasing if necessary. This procedure will eliminate profiles with a low number of photons, however if the profiles are short this can also eliminate good profiles. You can check the amount of profiles eliminated in the information window in the same module.

e) When ready with the filter subsets press the green button “Process profiles and filters”, this will take some time, when ready the number of excluded profiles will appear in the information window directly below. Change the minimum number of photons and the other subsets if too many profiles are eliminated. The profiles are automatically saved as a .mat file in the same folder where the previous .mat files were saved.

S4.2.6: Module to display the profiles and data selection.

a) After the filter are applied and the profiles extracted press the grey button "Display filtered data". All the filtered profiles will be displayed in the plot window.

b) Go to the left listbox below quick data selection and select one profile. If you are working with ATL03/ATL08 data you can activate the tick button "classified photons" to display vegetation, ground, and outliers.

c) Navigate through the list of profiles in order to visualize and select the best ones. When you find a good profile (a profile that clearly display the topography without gaps and too much noise) add it to the listbox at the right side by pressing the "add" button. You can also remove it if you change opinion.

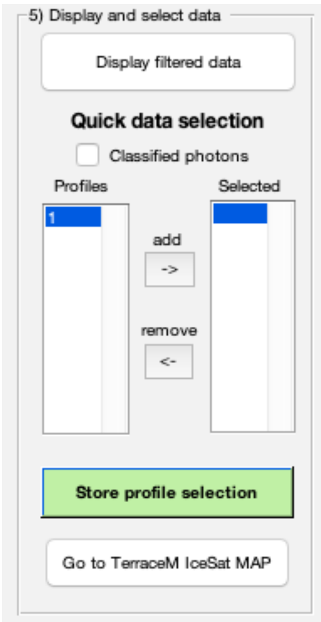

Figure S20: TerraceM ICESat Process, display and select filtered profiles

d) When your selection of profiles is ready press the green button "Store profile selection" and select a directory where to save the profiles, usually the same directory where you saved the previous .mat files.

e) now all is done in Terrace_ICESat_Process, press the grey button "Go to TerraceM_ICESat_MAP" to map the marine terraces in the selected profiles.

S4.3: TerraceM_Icesat_MAP

With TerraceM Icsesat_Map GUI the user can map terraces in the previously selected profiles. The interface follows a workflow from top to bottom. Important information to guide the users is displayed in the information window below the plot area.

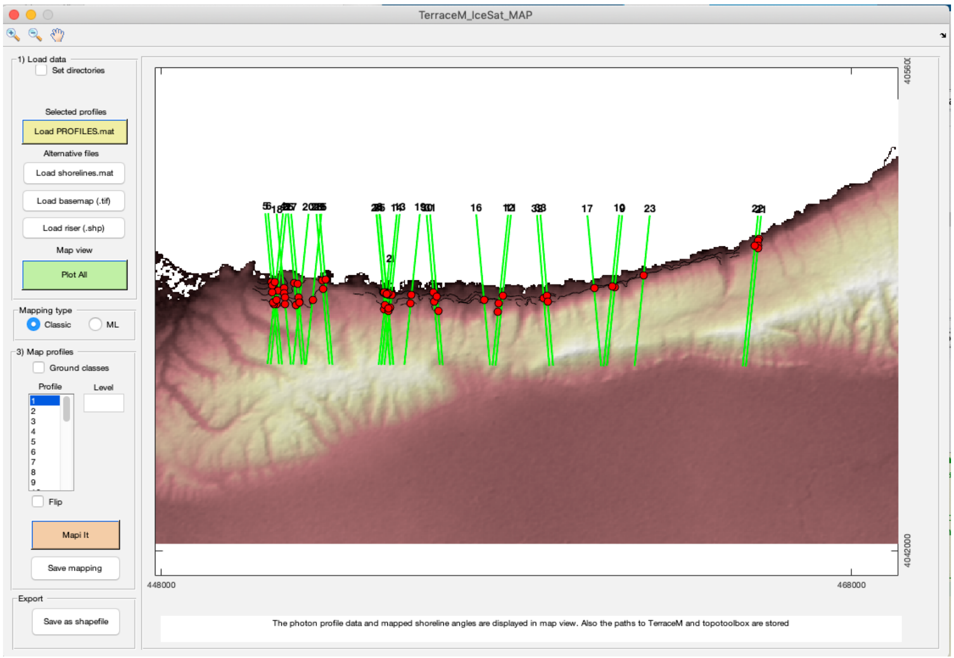

Figure S21: TerraceM ICESat MAP interface

S4.3.1: Load Data. If this is the first time running TerraceM_ICESat_MAP activate the tick button "Set directories"

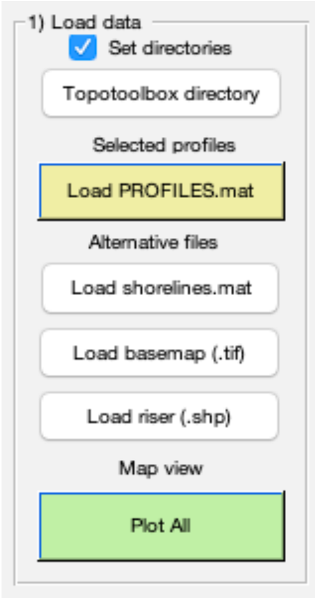

Figure S22: TerraceM ICESat MAP load data and set directories

a) set the path to the topotoolbox folder (located in the main TerraceM directory). You can load a topography in UTM (WGS84) CRS and also a polyline shapefile containing the risers (Using the same projection)

b) load data for mapping, press the yellow button “Load Profiles.mat” and navigate to your selected profiles. This file is required for mapping. Optionally you can load previously mapped shorelines, a basemap (topography in .tif format and UTM coordinates), and inner edges mapped using a polylines in any GIS software.

c) When ready loading your files press the green button “Plot All”. This will display all the data in the plot window and will populate the listbox in module 3.

S4.3.2: Select a mapping method.

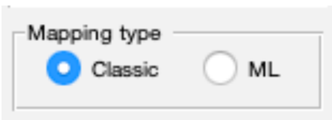

Figure S23: TerraceM ICESat MAP select mapping method

a) The user can select manual mapping method (Classic), which uses four points marked on the plot window, two points defining the paleo-cliff and two points defining the paleo-platform. The points are marked from right to left, first the cliff (top and bottom) and then the platform (right to left).

b) The second method is machine learning (ML). The user marks a squared area by dragging the mouse from one corner to the opposite corner, the area should encompass the paleo-cliff and paleo-platform of a single marine terrace. This can be repeated as needed to refine the result.

S4.3.3: Map the profiles. If you are working with ATL03/ATL08 data the photon classification will be displayed by activating the tick button at the top (ground classes), then the displayed point classes are controlled with the radiobuttons below. By default, the "ground class" is used for mapping the marine terraces, independently of the point classes displayed.

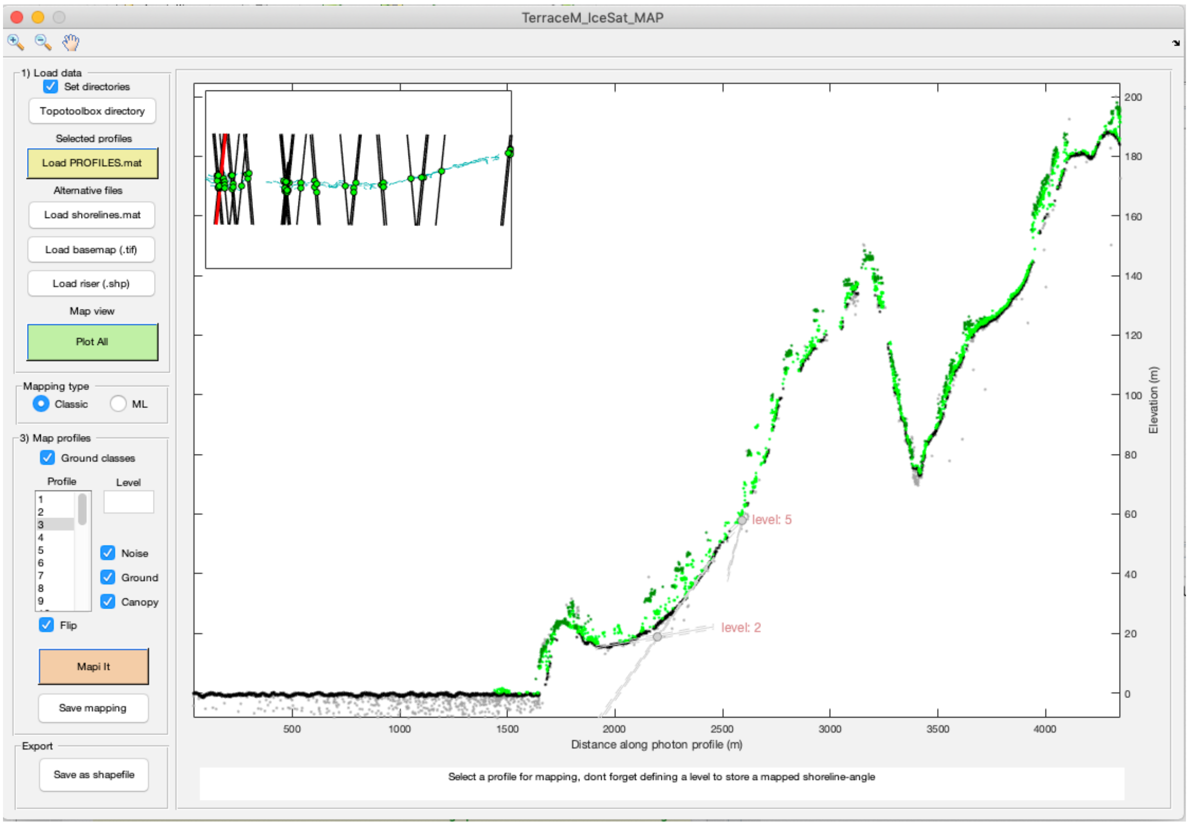

Figure S24: TerraceM ICESat MAP selected profile ready to map

a) After selecting any profile in the listbox, the profile will be displayed in the plot window. If shoreline angles were previously mapped, they will be also displayed in red or blue color depending of the mapping method.

b) When ready to map select a profile and assign a level number in the Level text box e.g. 1.

c) Then press Map it. Depending if Classic or ML is selected the mapping method will follow the procedures described in Step 2 (mapping method).

d) If you are satisfied with the shoreline angle mapped press save mapping. If you are not satisfied select the same profile in the listbox and press “Map it” again. I you want map another profile just select it in the listbox. Not all the profiles need to be mapped, map those where marine terrace morphology is detectable.

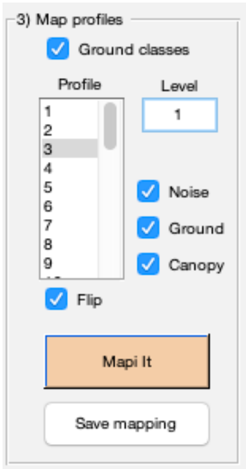

Figure S25: TerraceM ICESat MAP select profile and data display before “map it”

S4.3.4: Export module. The user press the button “Save as shapefile” to load the freshly mapped shoreline angles in any GIS platform. You can do this at any moment, every time you press this button the shapefile will be updated. In QGIS this might require unloading and loading the file for correct update.

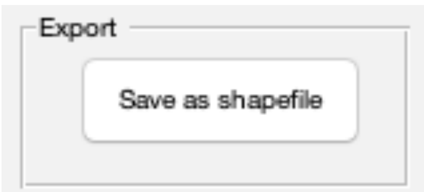

Figure S26: TerraceM ICESat MAP save the mapping results as shapefile

S4.4: TerraceM_ICESat_BAT

With TerraceM ICESat_BAT GUI the user can extract shallow bathymetry profiles from IceSat-2 ATL03 and ATL06 photon data.

S4.4.1: Load data and set directories. Is a requirement to load the matlab® Track (.mat format, e.g TRACK_ATL03.mat) of the ATL03 product. This file was previously created by TerraceM_IceSat_Process. The path to topotoolbox folder should be indicated if a basemap topography is loaded.

S4.4.2: Filter data and create the profiles. The data can be filter by minimum number of photons in a profile and photon confidence. When analysing bathymetry, it is recommended using low confidence values because Originally IceSat-2 is not designed for bathymetry and the photons that reach the seafloor are considered low confidence. I recommend using confidence 1 in order to exclude very noisy profiles. The beam strength “Weak” and “Strong”, both perform good when estimating land elevation, so it is recommended using both Weak/Strong, in order to include most of the profiles available.

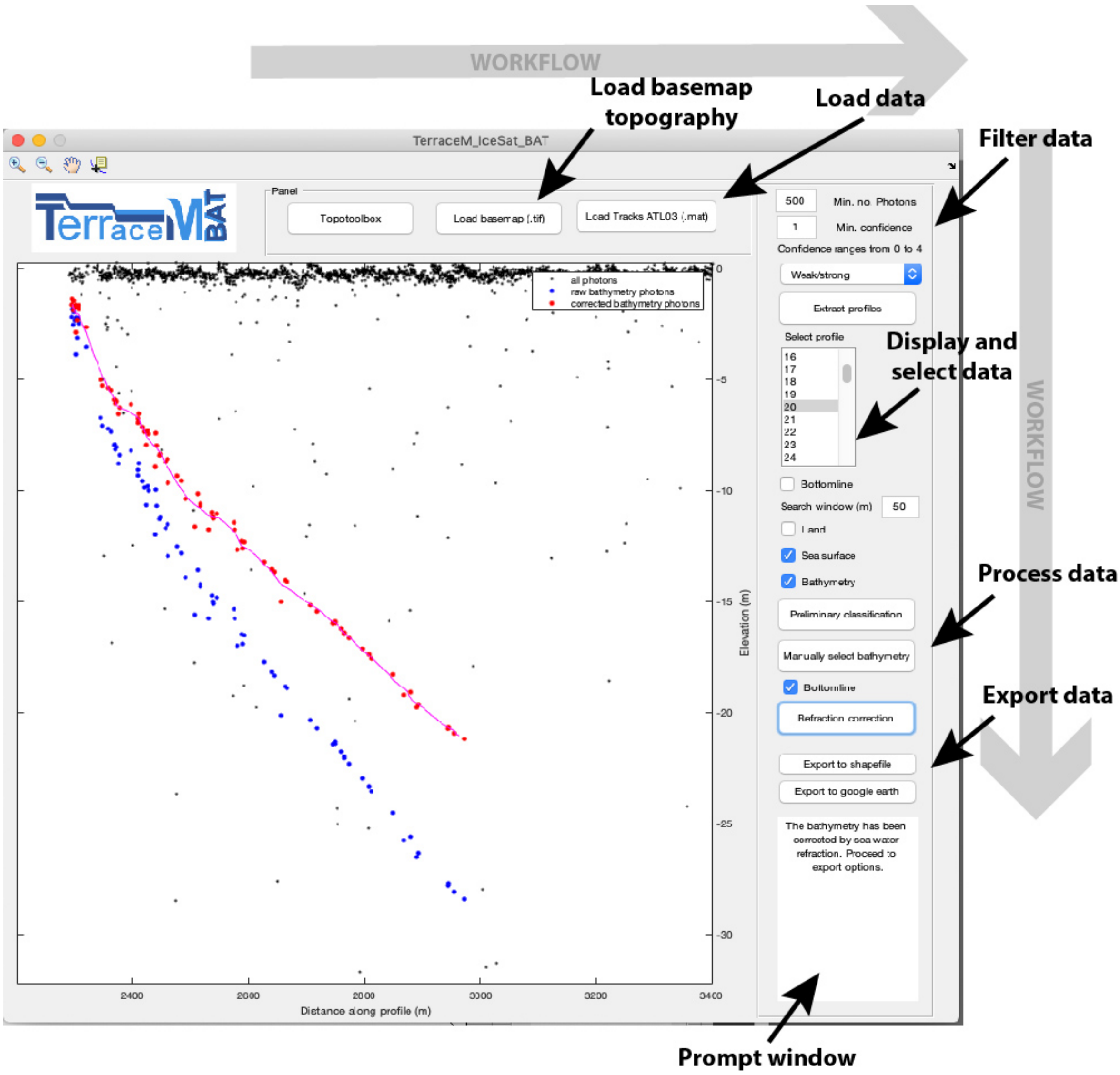

Figure S27: TerraceM ICESat BAT interface

S4.4.3: Preliminary location and profile view. The listbox allows selecting profiles interactively. The idea is to find those profiles that better display bathymetry photons within the typical noise in the nearshore. Usually, clusters and aligned photons denotes the seafloor (see figure).

S4.4.4: Process data and export. Preliminary photon classification is the first step to isolate the bathymetry photons. Manually select bathymetry allows selecting manually the seafloor returns from the rest of the noise photons. After clicking the button "Manually select bathymetry" click on the plot and press enter, this will activate a crosshair cursor. Using this cursor mark the contour of a polygon that enclose the clearest seafloor returns. When ready press the right mouse button to close the polygon. If you are satisfied with the manual mapping press "Refraction correction", this applies a vertical and horizontal correction by sea water refraction. When ready export to shapefile or excel. Additional information is provided in the window prompt.

S5. TerraceM Python

TerraceM-3 offers new additions that will help to increase the precision and accuracy of marine terrace mapping; however, its usage is still restricted to the MATLAB® environment. To tackle this limitation, TerraceM-3 mapping interface has been extended to work in Python® without the need of a MATLAB® license. The code is based on Geopandas and has been developed using a graphic user interface base on Tkinter, which can be deployed in Windows, Mac, and Linux systems. Some specific python libraries are required for functionality, such as numpy, rasterio and matplotlib. Just like TerraceM_MAP for MATLAB®, the new Python® version works with swath profiles which are extracted and displayed for mapping. TerraceM_Python uses as inputs the swath profiles as shapefiles created in any GIS platform and a topography digital elevation model in TIF format and UTM reference system. In contrast to the MATLAB® version, swath extraction and display is at least 50% faster and enables processing and mapping large amounts of profiles and big sized topography files.

References

Abdalati, W., Zwally, H. J., Bindschadler, R., Csatho, B., Farrell, S. L., Fricker, H. A., Harding, D., Kwok, R., Lefsky, M., and Markus, T.: The ICESat-2 laser altimetry mission, Proceedings of the IEEE, 98, 735–751, 2010.

Field, C., Martino, A., and Ramos-Izquierdo, L.: ICESat-2/ATLAS instrument linear system impulse response, Earth Space Sci., 10504651, https://doi.org/10./essoar, 2020.

Jasinski, M., Stoll, J., Hancock, D., Robbins, J., Nattala, J., Moriso, J., Jones, B., Ondrusek, M., Pavelsky, T., and Parrish, C.: ATLAS/ICESat-2 L3B mean inland surface water data, NASA National Snow Ice Data Center Distributed Active Archive Center data set, ATL22. 001, 2021.

Khalsa, S. J. S., Borsa, A., Nandigam, V., Phan, M., Lin, K., Crosby, C., Fricker, H., Baru, C., and Lopez, L.: OpenAltimetry - rapid analysis and visualization of Spaceborne altimeter data, Earth Science Informatics, 15, 1471–1480, 10.1007/s12145-020-00520-2, 2022.

Markus, T., Neumann, T., Martino, A., Abdalati, W., Brunt, K., Csatho, B., Farrell, S., Fricker, H., Gardner, A., and Harding, D.: The Ice, Cloud, and land Elevation Satellite-2 (ICESat-2): science requirements, concept, and implementation, Remote sensing of environment, 190, 260–273, 2017.

Neuenschwander, A. and Pitts, K.: The ATL08 land and vegetation product for the ICESat-2 Mission, Remote sensing of environment, 221, 247–259, 2019.

Neuenschwander, A., Pitts, K., Jelley, B., Robbins, J., Markel, J., Popescu, S., Nelson, R., Harding, D., Pederson, D., Klotz, B., and Sheridan, R.: ATLAS/ICESat-2 L3A Land and Vegetation Height, Version 6, NASA National Snow and Ice Data Center Distributed Active Archive Center [dataset], 10.5067/ATLAS/ATL08.006, 2023.

Neumann, T., Brenner, A., Hancock, D., Robbins, J., Gibbons, A., Lee, J., Harbeck, K., Saba, J., Luthcke, S., and Rebold, T.: ATLAS/ICESat-2 L2A Global Geolocated Photon Data, Version 6, NASA National Snow and Ice Data Center Distributed Active Archive Center [dataset], 10.5067/ATLAS/ATL03.006, 2023.

Smith, B., Adusumilli, S., Csath, B. t., Felikson, D., Fricker, H., Gardner, A., Holschuh, N., Lee, J., Nilsson, J., Paolo, F., Siegfried, M., Sutterley, T., and Team, T. I.-S.: ATLAS/ICESat-2 L3A Land Ice Height, Version 6, NASA National Snow and Ice Data Center Distributed Active Archive Center [dataset], 10.5067/ATLAS/ATL06.006, 2023.