
PC_geomorph_roughness

Pre-process and classify lidar or SfM point-cloud data for processing with *PC_geomorph_roughness*

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1 Point Cloud (PC) Geomorphologic roughness analysis

This document-in-manual-style roughly outlines the steps necessary to take an unclassified, raw point cloud (PC), perform a ground classification using commercial or open-source tools, generate Digital Elevation Models (DEMs), calculate PC statistics for selected seed points (user inputs spacing), and generate interpolated GeoTIFF files for further processing and analysis.

The algorithm and an application for this code is described in: *Bingham, N., Bookhagen, B., Johnson, K., and Chadwick, O. (in review): Use of lidar point cloud data to assess human-induced erosion and loss of vegetation cover on contrasting lithologies*

When using the code, please cite this paper!

2 Installation

The preferred system to run this code is a Linux derivative, but using OS X or the Windows 10 Bash setup with Ubuntu will work as well. It will require additional work to make the code function on a Windows 10 only system without bash support.

2.1 Installation on Windows 10

Installation works best, if you use the Windows 10 Bash. There are several resources available on the internet that explain the [bash setup](#). After the reboot, wget [miniconda](#) for [Linux 64 bit](#) and install:

```
wget https://repo.anaconda.com/miniconda/Miniconda3-latest-Linux-x86_64.sh  
bash Miniconda3-latest-Linux-x86_64.sh
```

Next, call:

```
conda config --prepend channels conda-forge/label/dev  
conda config --prepend channels conda-forge  
conda create -y -n PC_py3 python=3.6 pip scipy pandas numpy matplotlib \  
scikit-image gdal pdal xarray packaging ipython multiprocessing \  
h5py lastools pykdtree spyder gmt=5* imagemagick
```

Activate the environment and install laspy

```
source activate PC_py3  
pip install laspy
```

If you have LAStools installed, set the path within the bash.

```
export PATH=/mnt/c/LAStools/bin:$PATH
```

2.2 Installation on Linux

This is a Python 3.x code that will run on any OS, which supports the packages. It runs and has been tested on Linux (Ubuntu/Debian), Windows 10, and Mac OS X. We are using [conda/miniconda](#) to install the required packages, which can be [downloaded here](#). Follow [these instruction](#) to get miniconda installed. In short:

```
wget https://repo.anaconda.com/miniconda/Miniconda3-latest-Linux-x86_64.sh  
bash Miniconda3-latest-Linux-x86_64.sh
```

You will need several packages for python to run this code. These are standard packages and are included in all distributions. We create an environment called *PC_py3* (PointCloud-python3) in the following way (currently we are using Python 3.6, but 3.7 should work equally well):

```
conda config --prepend channels conda-forge/label/dev  
conda config --prepend channels conda-forge  
conda create -y -n PC_py3 python=3.6 pip scipy pandas numpy matplotlib \  
scikit-image gdal pdal xarray packaging ipython multiprocessing \  
h5py lastools pykdtree spyder gmt=5* imagemagick
```

You can active this environment on the command line with `source activate PC_py3`.

You don't need ipython or spyder to run this code and you can remove these repositories in the command line above, but they usually come in handy. Also, we are installing GMT5 for visualization purposes. If you don't plan to generate maps and/or use GMT, you can safely remove *gmt=5** and *imagemagick* from the line above.

Next, Install a fast and simple LAS/LAZ reader/writer. You can do similar steps through *lastools*, but this interface is fairly simple to use. *Please note that laspy currently does not support writing LAZ files.*

```
source activate PC_py3  
pip install laspy
```

If you have issues with pip, see: [here](#).

This code uses [pykdtree](#). There are other KDTree implementations, for example [scipy.spatial.cKDTree](#). But pykdtree is faster (but doesn't allow you to save the results such as cKDTree). Because we aim at

processing very large point clouds, the pyKDTree algorithm is significantly faster for generating and querying the KDtree and will increase processing speed (we have run tests with 1e6 to 1e9 points).

2.3 Installation of *PC_geomorph_roughness*

After the setup either on Ubuntu or Windows 10 Bash, install the repository into your favorite github directory, for example ~/github:

```
cd ~/github  
git clone https://github.com/UP-RS-ESP/PC_geomorph_roughness
```

You are now ready to run the code from the command line.

2.4 Install LAStools

2.5 Install lidar2dem

The python-based tool [lidar2dem](#) is a Python2 based list of modules and script. This is a useful implementation if you aim to classify many files in individual directories and convert them to a DTM. A nice workflow is provided. To take full advantage of some of the code's capabilities, we first need to install a python2-based environment:

```
conda create -y -n PC_py2 python=2* pip scipy pandas numpy matplotlib \  
scikit-image gdal pdal xarray packaging ipython multiprocessing \  
h5py lastools pykdtree spyder gmt=5* imagemagick  
source activate PC_py2
```

Installation into the home directory (alternatively, if sudo rights are available, install into /usr/local/src):

```
source activate PC_py2  
pip install gippy  
cd ~  
git clone https://github.com/AppliedGeoSolutions/lidar2dems.git  
cd lidar2dems  
. ./setup.py install
```

You are now ready to use *l2d_classify* and other tools from the lidar2dem scripts.

2.6 Install points2grid

The code points2grid provides a useful environment for interpolating large, classified points. It does not classify a PC, but takes a classified PC and generates a DEM (or Digital Terrain Model) from it by local interpolation of the points. For more information see [OpenTopography points2grid webpage](#), the [CRREL github webpage](#), and follow the [Installation description](#). In short, these are:

```
source activate PC_py3
conda install libcurl
cd ~
mkdir bin
git clone https://github.com/CRREL/points2grid.git
cd points2grid
mkdir build
cd build
cmake .. -DCMAKE_INSTALL_PREFIX=~/
make -j
make install
```

Make sure to add the path `~/bin` to the path variable

```
export PATH=~/bin:$PATH
export LD_LIBRARY_PATH=~/lib:$LD_LIBRARY_PATH
```

and you may want to add this permanently to your `.bashrc`:

```
echo "export PATH=~/bin:$PATH" >> ~/.bashrc
echo "export LD_LIBRARY_PATH=~/lib:$LD_LIBRARY_PATH" >> ~/.bashrc
```

3 Point Cloud (PC) Classification

PC classification is not part of the manuscript and algorithm described. Here, we show two approaches how to ground-classify a PC. You may know of others (and there are certainly many different ways to ground-classify PCs).

We describe ground-classification using the commercial [LAStools](#) package and an open-source approach with [PDAL](#).

We focus on our analysis on three subcatchments in the Pozo catchments (example_01, example_01m example_03). An oblique view of the Pozo catchment illustrates the steep terrain and diverse landcover (Figure 1).

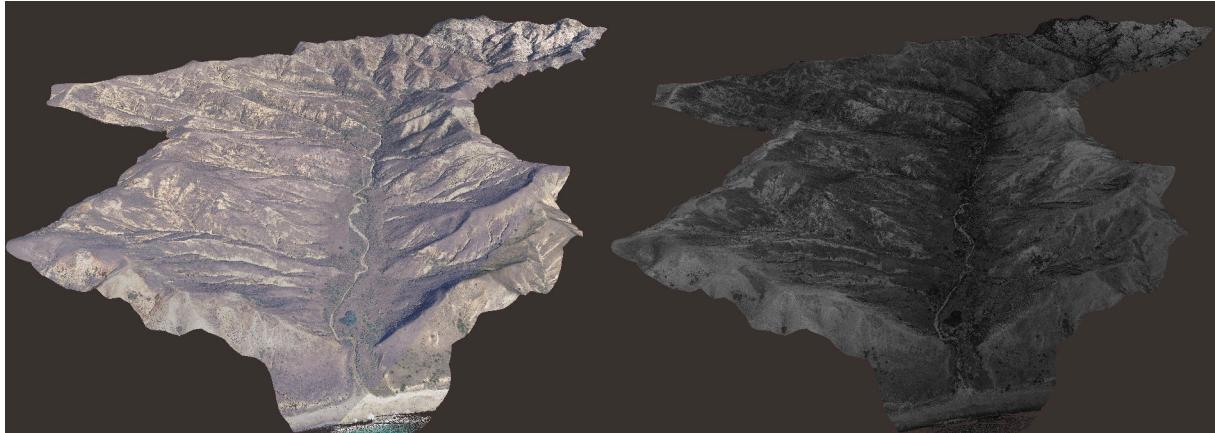


Figure 1: Oblique view of the Pozo catchment in the southwestern part of the Santa Cruz Island. For this area, we show the analysis of three subcatchments in [example_01](#), [example_02](#), and [example_03](#). The left image illustrate RGB colors taken from a recent airphoto and draped over the point clouds, the right view shows the intensity values of the NIR lidar. There are n=69,301,579 points (all points, no classification).

3.1 Classification with LAStools

NOTE: [LAStools](#) is a commercial code and requires a license to be fully functional. An alternative to LAStools is described using PDAL's implementation of SMRF.

First, we clip the catchment with [lasclip](#) from a larger LAZ file containing ~69 Mio. points for the southwestern part of Santa Cruz Island (Figure 1). These data are stored in file *Pozo_USGS_UTM11_NAD83_all_color_noel.laz* (not provided with these example, because it is too large for storage on github). But the entire dataset is freely available and can be obtained at [OpenTopography](#).

3.1.1 Clipping a PC

We use a shapefile in the same projection as the LAZ pointcloud to extract the subsetted, unclassified pointcloud. We have buffered this shapefile by 50m to make sure to include points from outside the drainage divide (derived from a 1m DEM) to avoid artifacts. Here we demonstrate this for catchment [example_01](#) (also called catchment 16).

NOTE: Because we run these examples on an Ubuntu system, we use wine. If you are on a Mac OSX, the commands will be similar. On a Windows system, you can just use the .exe files (e.g., lasinfo.exe - if you have set the path variable correctly as shown above).

```
cd example_01
```

```
wine /opt/LAStools/bin/lasclip.exe -i ../Pozo_USGS_UTM11_NAD83_all_color_noel.laz \
-poly Pozo_DTM_noveg_UTM11_NAD83_cat16_b50m.shp -o Pozo_USGS_UTM11_NAD83_cat16.laz
```

The resulting point cloud has 1,245,618 points. Often, PCs from other sources come with pre-classified points. These often have not been verified and we suggest to remove previous classification and user flags with [lasclassify](#).

```
wine /opt/LAStools/bin/lasclassify.exe -i Pozo_USGS_UTM11_NAD83_cat16.laz -olaz \
-set_user_data 0 -set_classification 0 -o Pozo_USGS_UTM11_NAD83_cat16_uncl.laz
```

Next, we obtain PC density information using [lasinfo](#):

```
wine /opt/LAStools/bin/lasinfo.exe -i Pozo_USGS_UTM11_NAD83_cat16_uncl.laz -nh -nv \
-nmm -cd

lasinfo (180422) report for 'Pozo_USGS_UTM11_NAD83_cat16_uncl.laz'
number of first returns: 1234002
number of intermediate returns: 149
number of last returns: 1236327
number of single returns: 1224860
covered area in square units/kilounits: 152992/0.15
point density: all returns 8.14 last only 8.08 (per square units)
    spacing: all returns 0.35 last only 0.35 (in units)
overview over number of returns of given pulse: 1224860 20255 503 0 0 0 0
```

3.1.2 Optional PC pre-processing

If you know you have a noisy dataset (for example from SfM data), filter by noise and isolated points:

```
wine /opt/LAStools/bin/lasnoise.exe -i Pozo_USGS_UTM11_NAD83_cat16_uncl.laz -step_xy 2 \
-step_z 1 -isolated 5 -olaz -o Pozo_USGS_UTM11_NAD83_cat16_uncln.laz
```

NOTE: If you have SfM data you likely will need to do additional pre-processing steps to clean up your point cloud.

3.1.3 PC ground classification

Next, we perform the actual PC ground classification using [lasground](#). There are many different options and these likely will need to be fine tuned and adjusted to your area. Make sure to read the [README](#) and understand the various parameters. Alternative to lasground you may consider using PDAL's implementation of SMRF (see below and [guide](#)).

```
wine /opt/LAStools/bin/lasground.exe -i Pozo_USGS_UTM11_NAD83_cat16_uncln.laz \
-by_flightline -wilderness -extra_fine -offset 0.25 -stddev 20 -step 1 -spike 0.5 \
-bulge 0.5 -olaz -o Pozo_USGS_UTM11_NAD83_cat16_clg.laz
```

In the above steps, we ground-classify the PC. Ground points are assigned the class=2. There are several options to chose from: We allow an extra offset of 0.25m (25cm) and thereby include points to the ground class that may otherwise be filtered out. This is based on visual inspection of the results. Because the the point cloud is fairly dense (~8 pts/m²), we use a step size of 1m (Figure 2).

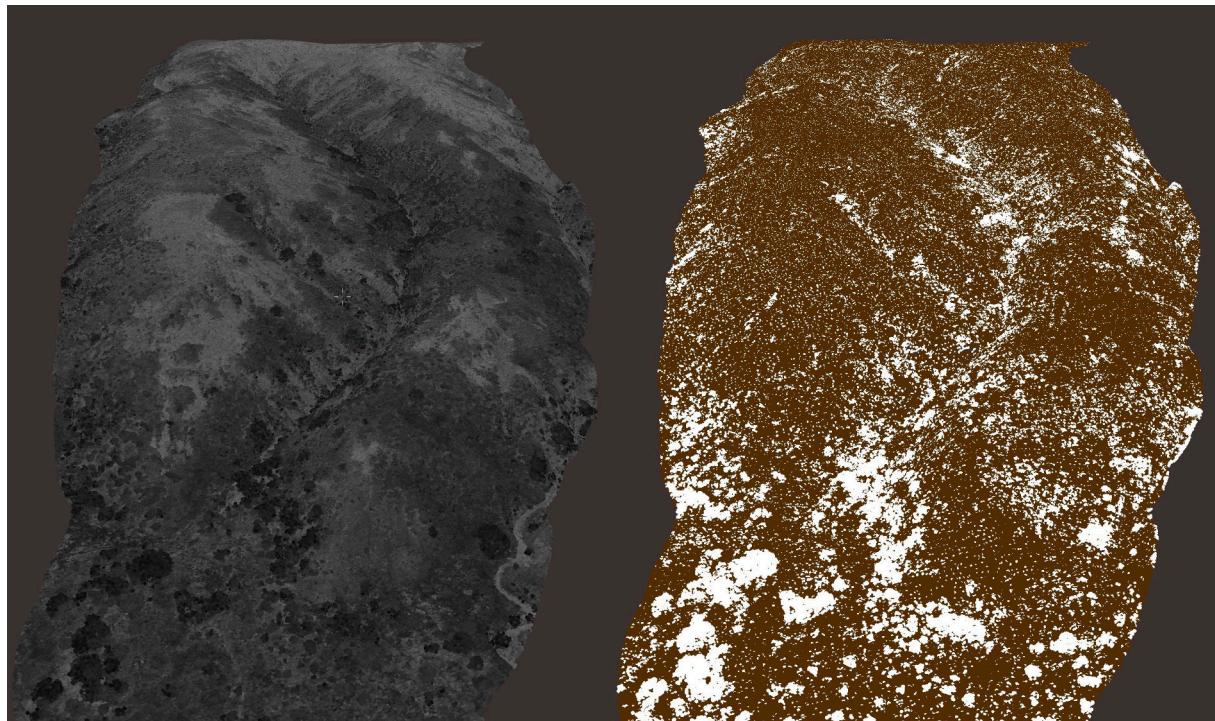


Figure 2: Oblique view of subcatchment 16 in the Pozo catchment. Left view shows the intensity image, right side shows the ground-classified PC (white points are unclassified, brown-yellow colors indicate ground points). There are n=1,245,618 total points (all points, no classification), 231,928 unclassified (class=1), and 1,013,690 ground (class=2) points.

If you prefer to use a stricter classification (i.e., fewer ground points are identified), you can use the standard parameters (but these are not fine tuned to the rough terrain of the Santa Cruz Island).

```
wine /opt/LAStools/bin/lasground.exe -i Pozo_USGS_UTM11_NAD83_cat16_uncln.laz \
-by_flightline -wilderness -extra_fine -olaz -o \
Pozo_USGS_UTM11_NAD83_cat16_clg_normal.laz
```

NOTE: You should always visually inspect your classified points using [displaz](#) or [CloudCompare](#) or something similar to make sure that the point-cloud classification performed well in the crucial areas. If you are not satisfied with your classification, you may want to experiment with [lasground_new](#):

```
wine /opt/LAStools/bin/lasground_new.exe -i Pozo_USGS_UTM11_NAD83_cat16_uncln.laz \
-wilderness -extra_fine -olaz -o Pozo_USGS_UTM11_NAD83_cat16_clg_lasground_new.laz
```

NOTE: We emphasize the importance of properly classifying your point cloud. If you have all natural terrain, it will be important to distinguish between ground and vegetation. In urban or suburban areas, you may want to further distinguish buildings from bare-earth lidar returns. It is essential that you spent time on the classification before proceeding with the analysis.

Once you have identified the best point-cloud classification, you can save only the ground points to a separate file (i.e., a file containing only ground points). This will be used for the analysis with *PC_geomorph_roughness*.

```
wine /opt/LAStools/bin/las2las.exe -i Pozo_USGS_UTM11_NAD83_cat16_clg.laz -keep_class \
2 -olaz -o Pozo_USGS_UTM11_NAD83_cat16_clg_cl2.laz
```

3.1.4 PC vegetation classification

For some applications it may be useful to have a vegetation class defined. This can be achieved in several ways and the most straight forward approach is to rely on [lasclassify](#). This is not required for running *PC_geomorph_roughness*, but still may come in useful. In order for lasclassify to work, you will need to store the height above ground for every point. This can be achieved by running lasground with the option *-compute_height*. Assuming your lasground parameters are the first example from above (without *-compute_height*), we use:

```
wine /opt/LAStools/bin/lasheight.exe -i Pozo_USGS_UTM11_NAD83_cat16_clg.laz -olaz -o \
Pozo_USGS_UTM11_NAD83_cat16_clgh.laz
```

Alternatively, you can attempt to run the height computation during the lasground classification, but this prevents the *-by_flightline* option:

```
wine /opt/LAStools/bin/lasground.exe -i Pozo_USGS_UTM11_NAD83_cat16_uncln.laz \
-wilderness -extra_fine -offset 0.25 -stddev 20 -step 1 -spike 0.5 -bulge 0.5 \
-olaz -compute_height -o Pozo_USGS_UTM11_NAD83_cat16_clgh.laz
```

The file containing height information stored in the user-data flag can be used for further classification:

```
wine /opt/LAStools/bin/lasclassify.exe -i Pozo_USGS_UTM11_NAD83_cat16_clgh.laz \
-ground_offset 0.5 -planar 0.1 -rugged 0.6 -olaz -o \
Pozo_USGS_UTM11_NAD83_cat16_clghc.laz
```

The important options here are *-ground_offset* that determines the minimum height of vegetation or buildings. For the Santa Cruz Island, this can be set to a lower value of 0.5m. This will only consider points 0.5m above the ground to determine vegetation or buildings (often 1.5 or 2m are used). The options *-planar* and *-rugged* allow to control the identification of roofs (planar) and trees (rugged). In the study area, no buildings exist, but different vegetation types, so we have increased the rugged value. The results indicate a reasonable classification of vegetation (Figure 3).



Figure 3: Oblique view of the lower part of subcatchment 16 in the Pozo catchment. Left view shows the color image, middle image is the lidar intensity, right side shows the ground and vegetation-classified PC (brown-yellow colors indicate ground, green vegetation, and white points are unclassified). Further optimization could increase the detection limit of vegetation to include some of the lower bushes by decreasing the *-ground_offset* parameters (e.g., *-ground_offset* 0.35) and increasing the *-rugged* parameter (e.g., *-rugged* 0.8).

3.1.5 DTM from ground-classified PCs

Next, we generate a DTM from the ground-classified point cloud using [blast2dem](#). This creates a TIN model of the surfaces and samples this at the required intervals. The output is stored in the subdirectory *dtm_interp* (interpolated Digital Terrain Model).

```
mkdir dtm_interp
wine /opt/LAStools/bin/blast2dem.exe -keep_class 2 -utm 11N -nad83 -meter \
-elevation_meter -merged -step 1 -i Pozo_USGS_UTM11_NAD83_cat16_clg_cl2.laz -o \
dtm_interp/Pozo_USGS_UTM11_NAD83_cat16_clg_cl2_1m.tif
```

If you intend to create a hillshade image for visualization, for example in QGIS, use:

```
wine /opt/LAStools/bin/blast2dem.exe -keep_class 2 -hillshade -utm 11N -nad83 -meter \
-elevation_meter -merged -step 1 -i Pozo_USGS_UTM11_NAD83_cat16_clg_cl2.laz -o \
dtm_interp/Pozo_USGS_UTM11_NAD83_cat16_clg_cl2_1m_HS.tif
```

In order to compare the outputs from the other classification schemes, we perform the same gridding on the other ground-classified PC (lasground_normal and lasground_new):

```
wine /opt/LAStools/bin/blast2dem.exe -keep_class 2 -utm 11N -nad83 -meter \
-elevation_meter -merged -step 1 -i Pozo_USGS_UTM11_NAD83_cat16_clg_normal.laz -o \
dtm_interp/Pozo_USGS_UTM11_NAD83_cat16_clg_cl2_normal_1m.tif
wine /opt/LAStools/bin/blast2dem.exe -keep_class 2 -utm 11N -nad83 -meter \
-elevation_meter -merged -step 1 -i \
Pozo_USGS_UTM11_NAD83_cat16_clg_lasground_new.laz -o \
dtm_interp/Pozo_USGS_UTM11_NAD83_cat16_clg_cl2_\
lasground_new_1m.tif
```

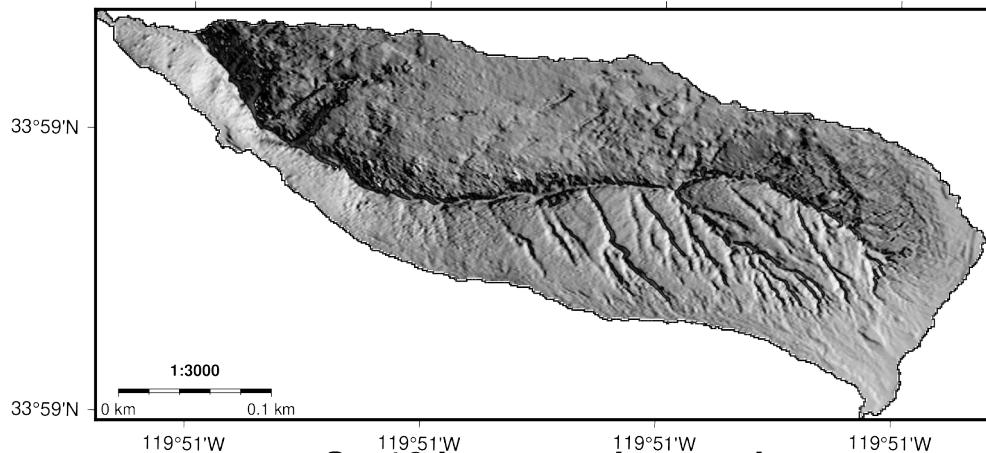
The resulting grids (Figures 4 and 5) indicate some differences (hillshade and DEM differences), but overall the classifications are comparable. Still, for detailed PC analysis it is important to have especially the low and high points properly classified.

NOTE: Before we can compare the grid, we will need to ensure that they are aligned to each other. The safest (and easiest) way of doing that is to make certain that the UTM coordinates of the grid (or GeoTIFF) is aligned with integer UTM coordinates. Second, we also want to cut the regions outside the catchment to avoid including border artifacts.

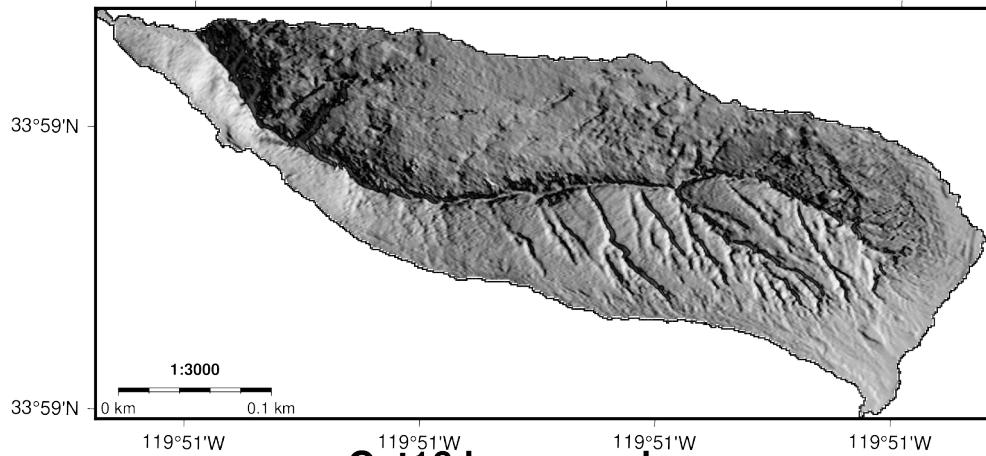
These steps have been included in the [GMT bash shell file](#). This can be achieved with:

```
DEM1=dtm_interp/Pozo_USGS_UTM11_NAD83_cat16_clg_cl2_1m.tif
SHAPEFILE=Pozo_DTM_noveg_UTM11_NAD83_cat16.shp
gdalwarp $DEM1 foo.tif -tap -tr 1 1 -r bilinear -cutline $SHAPEFILE -crop_to_cutline \
-co COMPRESS=DEFLATE -co ZLEVEL=7 -co predictor=3
```

Cat16 lasground adjusted



Cat16 lasground normal



Cat16 lasground new

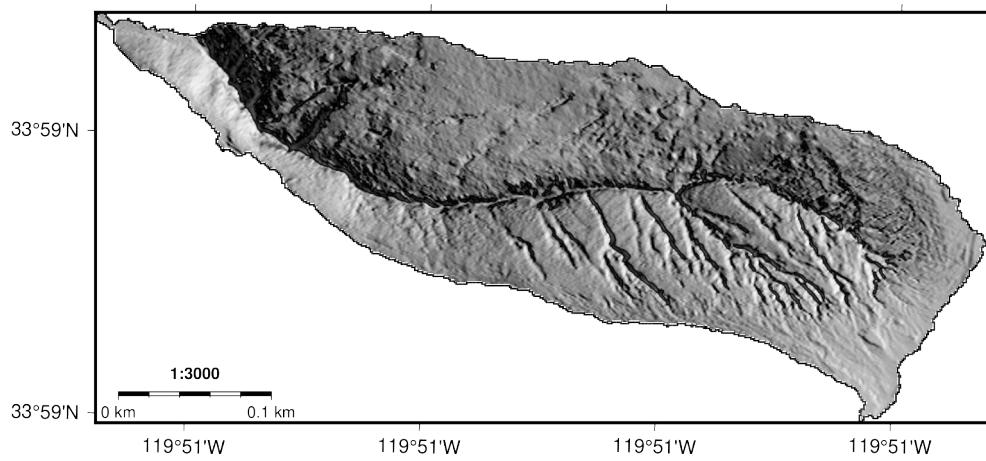


Figure 4: Map view of the adjusted lasground (top), normal lasground (middle), and lasground_new (bottom) outputs. Small differences are visible. This map comparison has been created with GMT (see [GMT script](#)).

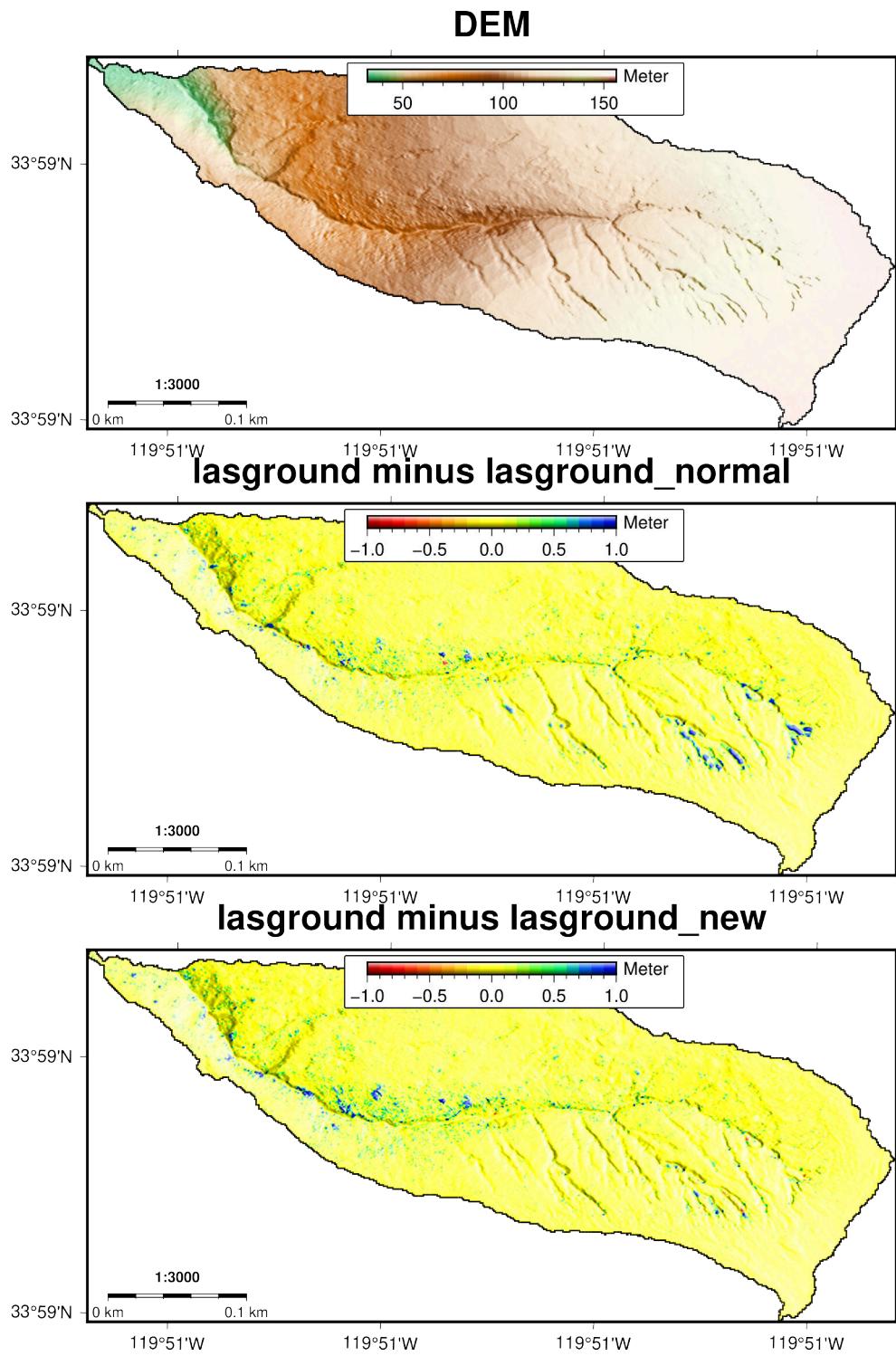


Figure 5: Map view of the difference (Delta H) between adjusted lasground and lasground-normal (middle), and lasground_new (bottom) outputs. Small differences are visible, especially where vegetation cover is high. This map comparison has been created with GMT (see [GMT script](#)).

3.1.6 Comparison of ground-classified PCs

A more direct way of comparison at the point-cloud level is to calculate the [Hausdorff Distance](#). Here we use the adjusted lasground classification as a reference PC and first create ground-classified LAZ files:

```
wine /opt/LAStools/bin/las2las.exe -i Pozo_USGS_UTM11_NAD83_cat16_clg.laz -keep_class \
2 -olaz -o Pozo_USGS_UTM11_NAD83_cat16_clg_cl2.laz
wine /opt/LAStools/bin/las2las.exe -i \
Pozo_USGS_UTM11_NAD83_cat16_clg_lasground_new.laz -keep_class 2 -olaz -o \
Pozo_USGS_UTM11_NAD83_cat16_clg_lasground_new_cl2.laz
wine /opt/LAStools/bin/las2las.exe -i Pozo_USGS_UTM11_NAD83_cat16_clg_normal.laz \
-keep_class 2 -olaz -o Pozo_USGS_UTM11_NAD83_cat16_clg_normal_cl2.laz
pdal hausdorff Pozo_USGS_UTM11_NAD83_cat16_clg_cl2.laz \
Pozo_USGS_UTM11_NAD83_cat16_clg_normal_cl2.laz
pdal hausdorff Pozo_USGS_UTM11_NAD83_cat16_clg_cl2.laz \
Pozo_USGS_UTM11_NAD83_cat16_clg_lasground_new_cl2.laz
```

The Hausdorff distance between the PCs classified with the adjusted parameters and with standard parameters is:

```
{
  "filenames": [
    "Pozo_USGS_UTM11_NAD83_cat16_clg_cl2.laz",
    "Pozo_USGS_UTM11_NAD83_cat16_clg_normal_cl2.laz"
  ],
  "hausdorff": 5.090078585,
  "pdal_version": "1.7.2 (git-version: a71df1)"
}
```

The Hausdorff distance between the PCs classified with the adjusted parameters and with a revised version of lasground is:

```
{
  "filenames": [
    "Pozo_USGS_UTM11_NAD83_cat16_clg_cl2.laz",
    "Pozo_USGS_UTM11_NAD83_cat16_clg_lasground_new_cl2.laz"
  ],
  "hausdorff": 3.1808961,
  "pdal_version": "1.7.2 (git-version: a71df1)"
}
```

3.2 Processing with PDAL

PDAL is an open-source point cloud library that provides easy access to the [PCL](#). It is very powerful, but not specifically designed to process lidar or SfM PCs. However, it provides some simple approaches to ground-classify terrain that we will explore here *NOTE: Vegetation classification with PDAL is possible, but requires several steps. These are not covered in this manual.*

3.2.1 Ground classification with PDAL's implementation of SMRF

We rely on the Simple Morphological Filter [SMRF](#) that can be accessed through `pdal translate` (or use your own pipeline). There is a step-by-step [instruction](#).

```
pdal translate \
  Pozo_USGS_UTM11_NAD83_cat16.laz \
  -o Pozo_USGS_UTM11_NAD83_cat16_smrf.las \
  smrf
```

NOTE: On some miniconda/anaconda installation, the writing to LAZ (compressed LAS) files is not supported. Change the output filename to .las instead.

There are several options to adjust, especially `-filters.smrf.scalar`, `-filters.smrf.slope`, `-filters.smrf.threshold`, and `-filters.smrf.window`. But the standard options provide reasonable results (Figure 6).

If you would like to save ground-class only points to a separate file, use the range filter:

```
pdal translate Pozo_USGS_UTM11_NAD83_cat16_smrf.las -o \
  Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2.las
range --filters.range.limits="Classification[2:2]"
```

You can combine this with the ground-classification into:

```
pdal translate \
  Pozo_USGS_UTM11_NAD83_cat16.laz \
  -o Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2.las \
  smrf range --filters.range.limits="Classification[2:2]"
```

In addition, you can include a simple outliers filter, ignore noise points (usually class=7) and save only the ground-classified points:

```
pdal translate \
  Pozo_USGS_UTM11_NAD83_cat16.laz \
  -o Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2.las \
```

```

outlier smrf range \
--filters.outlier.method="statistical" \
--filters.outlier.mean_k=8 \
--filters.outlier.multiplier=3.0 \
--filters.smrf.ignore="Classification[7:7]" \
--filters.range.limits="Classification[2:2]" \
--writers.las.compression=true

```

These results are comparable to the adjusted lasground parameters. The Hausdorff distance is comparable to LAStools' adjusted lasground classifications.

```

pdal hausdorff Pozo_USGS_UTM11_NAD83_cat16_clg_cl2.laz \
Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2.las

```

The Hausdorff distance is

```

{
  "filenames": [
    "Pozo_USGS_UTM11_NAD83_cat16_clg_cl2.laz",
    "Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2.las"
  ],
  "hausdorff": 4.910509139,
  "pdal_version": "1.7.2 (git-version: a71df1)"
}

```

3.2.2 Ground classification with PDAL's implementation of PMF

Next, we use the Progressive Morphological Filter [PMF](#) that can be accessed through pdal translate (or use your own pipeline):

```

pdal translate \
Pozo_USGS_UTM11_NAD83_cat16.laz \
-o Pozo_USGS_UTM11_NAD83_cat16_pmf.las \
pmf

```

The PMF filter will require setting additional parameters to use it for ground classification of the Pozo-catchment data (Figure 6).

```

pdal translate \
Pozo_USGS_UTM11_NAD83_cat16.laz \
-o Pozo_USGS_UTM11_NAD83_cat16_pmf.las \

```

```
pmf \
--filters.pmf.slope=2 \
--filters.pmf.exponential=false \
--filters.pmf.initial_distance=1 \
--filters.pmf.max_distance=4
```

Or combined into one longer code block with filtering and writing only class 2 points:

```
pdal translate \
Pozo_USGS_UTM11_NAD83_cat16.laz \
-o Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2.laz \
outlier pmf range \
--filters.outlier.method="statistical" \
--filters.outlier.mean_k=8 \
--filters.outlier.multiplier=3.0 \
--filters.pmf.ignore="Classification[7:7]" \
--filters.pmf.slope=2 \
--filters.pmf.exponential=false \
--filters.pmf.initial_distance=1 \
--filters.pmf.max_distance=4
--filters.range.limits="Classification[2:2]" \
--writers.las.compression=true
```

However, even with these aggressive filtering options, the PMF doesn't perform well in the very steep and rugged terrain of Santa Cruz Island.

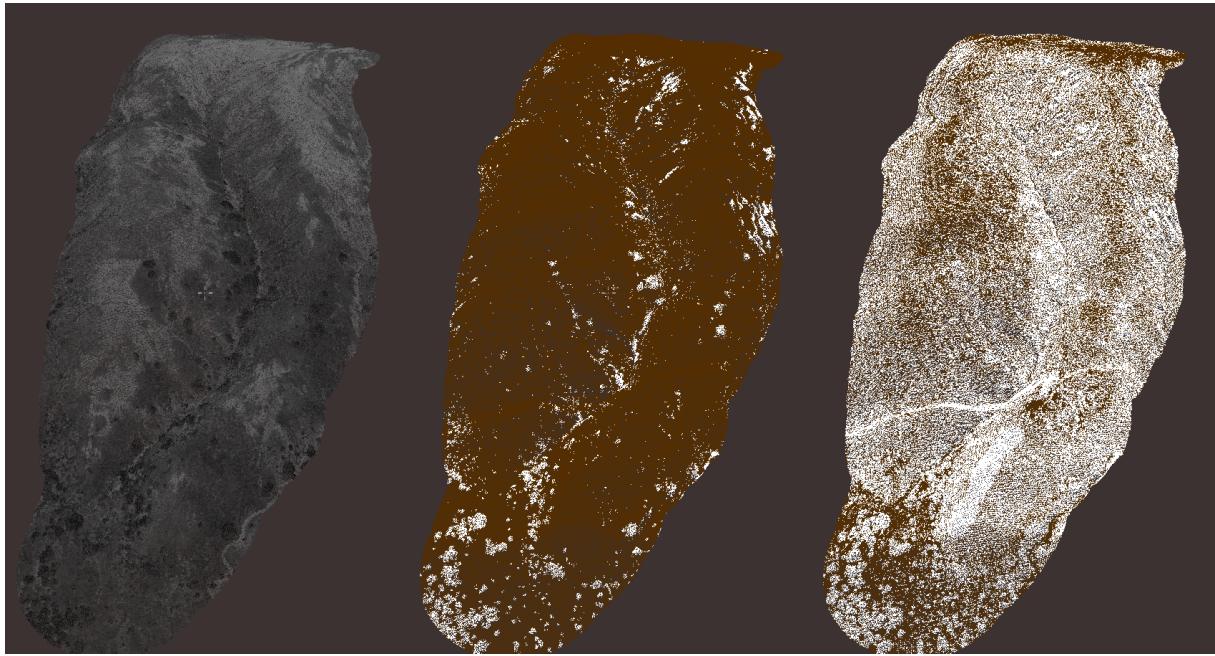


Figure 6: Oblique view of the lower part of subcatchment 16 in the Pozo catchment. Left view shows the lidar intensity image, middle is ground classification using PDAL’s implementation of SMRF, right image uses PDAL’s implementation of PMF (brown-yellow colors indicate ground and white points are unclassified). PMF will require setting additional parameters (see [PDAL filter webpage](#)), SMRF generates reasonable results with standard options.

3.2.3 Generating a DTM with PDAL

You can interpolate the ground-classified points from SMRF onto a gridded DEM using [pdal’s DTM pipeline](#). This approach relies on [writers.gdal](#), which in turn relies on [Points2Grid](#). For `gdal.writes` currently exists no command line support. Generate a file containing the necessary information to run a PDAL pipeline (call it `example01_gdal_smrf.json`). For the SMRF ground-classified file, we use:

NOTE: You may want to look into `otbcli_splitimage -in <in_file.tif> -out <out_file.tif>` if you have trouble reading the tif file.

```
{
  "pipeline": [
    "Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2.las",
    {
      "filename": "dtm_interp/Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2_Zmean.tif",
      "gdaldriver": "GTiff",
      "data_type": "float",
      "dimension": "Z",
    }
  ]
}
```

```

        "output_type": "mean",
        "resolution": "1.0",
        "type": "writers.gdal"
    }
]
}

```

Then run this with:

```
pdal pipeline --nostream example01_gdal_smrf.json
```

You can extract additional *output_type*, for example idw, stdev, count. Most importantly, you can overwrite existing parameters on the command line with:

```
pdal pipeline --nostream example01_gdal_smrf.json \
--writers.gdal.dimension="Intensity" \
--writers.gdal.data_type="float" \
--writers.gdal.output_type="mean" \
--writers.gdal.filename=\
"dtm_interp/Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2_intensity_mean.tif"
```

In a second step and in order to compare the interpolation algorithms from classified point clouds, we use the same PC (classified with the adjusted lasground parameters) and use blast2dem compared to the local points2grid interpolation scheme implemented in gdal.writer. We generate the pipeline *example01_gdal_lasground.json*:

```
{
"pipeline": [
    "Pozo_USGS_UTM11_NAD83_cat16_clg_cl2.laz",
    {
        "filename": "dtm_interp/Pozo_USGS_UTM11_NAD83_cat16_lasground_cl2_Zmean.tif",
        "gdaldriver": "GTiff",
        "data_type": "float",
        "dimension": "Z",
        "output_type": "mean",
        "resolution": "1.0",
        "type": "writers.gdal"
    }
]
}
```

Then run this with:

```
pdal pipeline --nostream example01_gdal_lasground.json
```

The output maps view of these interpolated surfaces are compared to other gridding methods (Figure 7).

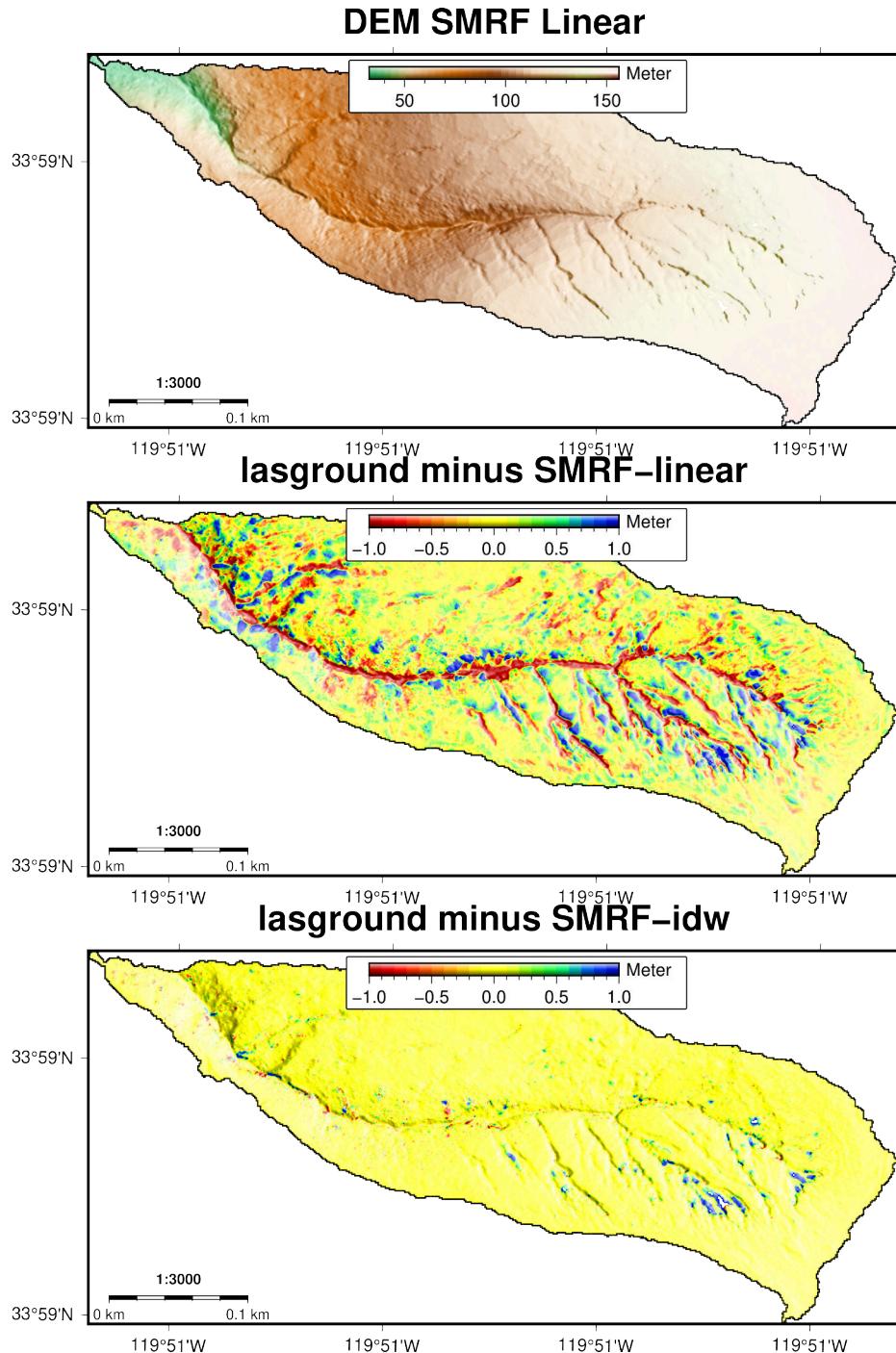


Figure 7: Map view of the PDAL SMRF classified DEM. Gridding was performed through the PDAL's writer.gdal approach. Intensity (top) and difference between adjusted lasground-classified PC and point2grid interpolated DTM (middle) is shown. Bottom illustrates the differences between the lasground-classified PC gridded with blast2dem minus gdal.writer. Note that points with high curvature appear to show the largest difference between the interpolation methods. See [GMT bash script](#).

3.2.4 Combined PDAL pipeline using filtering steps and SMRF classification

We can combine several steps in a PDAL pipeline to generate a ground-classified PC. In this pipeline, we first assign the class 0 to all points, perform an [Extended Local Minimum](#) filter, remove [outliers](#), perform [SMRF](#) ground segmentation and only write the ground-classified files to a file using a [range filter](#). The pipeline is stored in [example_01/example01_PDAL_SMRF_pipeline.json](#):

```
{  
  "pipeline": [  
    {  
      "type": "filters.assign",  
      "assignment": "Classification[:] = 0"  
    },  
    {  
      "type": "filters.elm",  
      "cell": 10.0,  
      "threshold": 2.0,  
      "class": 7  
    },  
    {  
      "type": "filters.outlier"  
    },  
    {  
      "type": "filters.smrf",  
      "last": true,  
      "ignore": "Classification[7:7]",  
      "cell": 1.0,  
      "slope": 0.2,  
      "window": 20,  
      "threshold": 0.8,  
      "scalar": 1.2  
    },  
    {  
      "type": "filters.range",  
      "limits": "Classification[2:2]"  
    }  
  ]  
}
```

The pipeline is run with the following command:

```
pdal translate Pozo_USGS_UTM11_NAD83_cat16.laz \  
  Pozo_USGS_UTM11_NAD83_cat16_SMRF_cl2.las --json example01_PDAL_SMRF_pipeline.json
```

This can be written to a DTM (nodata value=-9999) with the pipeline [example01_writers_gdal_smrf_Zmean_1m.json](#):

```
{  
  "pipeline": [  
    "Pozo_USGS_UTM11_NAD83_cat16_SMRF_cl2.las",  
    {  
      "filename": "dtm_interp/Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2_Zmean_1m.tif",  
      "gdaldriver": "GTiff",  
      "output_type": "mean",  
      "data_type": "float",  
      "resolution": "1.0",  
      "dimension": "Z",  
      "type": "writers.gdal"  
    }  
  ]  
}
```

and run with:

```
pdal pipeline --nostream example01_writers_gdal_smrf_Zmean_1m.json
```

It is recommended that you clip that DEM with the shapefile outlining the catchment to remove interpolation artifacts (remember, we have added a 50m buffer for that reason). There are different ways of doing this, here we use [gdalwarp](#). We first warp to a temporary file and then move the temporary file back to the original file. Note the option *-tap* that aligns the DEM to an integers-spaced UTM grid:

```
DEM_MN_GRD=dtm_interp/Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2_Zmean.tif  
SHAPEFILE=Pozo_DTM_noveg_UTM11_NAD83_cat16.shp  
gdalwarp $DEM_MN_GRD foo.tif -tap -tr 1 1 -r bilinear -cutline $SHAPEFILE \  
  -crop_to_cutline -co COMPRESS=DEFLATE -co ZLEVEL=7 -co predictor=3  
mv foo.tif $DEM_MN_GRD
```

3.2.5 Generating a DTM with from a PC with GDAL

Alternatively, you can interpolate the points from a point cloud to a gridded dataset using [gdal_grid](#). There are more versatile options available that allow to experiment with different algorithms. This requires that the LAZ file will be written to a CSV or similar file format that is readable by GDAL. In *PC_geomorph_roughness*, we use *gdal_grid* in the Python code to interpolate the seed points written as CSV, converted to VRT format to a grid.

First, write to CSV file using open-source las2las:

```
las2las -i Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2.las -o \
Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2.csv -oparse xyz
```

Second, add a header X,Y,Z,c,i,R,G,B and replace <space> with , :

```
sed -i '1s/^/X,Y,Z\n/' \
Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2.csv
sed -i 's/ /,/g' \
Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2.csv
```

Third, create a VRT file to control how gdal is reading this file. Create a file called *Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2.vrt* with content:

```
<OGRVRTDataSource>
  <OGRVRTLayer name="Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2">
    <SrcDataSource>Pozo_USGS_UTM11_NAD83_cat16_smrf_\
cl2.csv</SrcDataSource>
    <GeometryType>wkbPoint</GeometryType>
    <GeometryField encoding="PointFromColumns" x="X" y="Y" z="Z"/>
  </OGRVRTLayer>
</OGRVRTDataSource>
```

Fourth, we can convert the csv file to any GIS format. We use *ogr2ogr* for this. For example, converting it to a shapefile format (make sure to set proper EPSG information for proper projection):

```
ogr2ogr -oo KEEP_GEOM_COLUMNS=NO -oo GEOMETRY=AS_XYZ \
-oo SEPARATOR=COMMA -oo AUTODETECT_WIDTH=YES \
-oo HEADERS=AUTO -oo AUTODETECT_SIZE_LIMIT=0 \
-oo AUTODETECT_TYPE=YES \
-t_srs epsg:26911 -s_srs epsg:26911 \
Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2.shp \
Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2.vrt
```

Fifth, the shapefile can be interpolated to a grid using *gdal_grid*. We need the following parameters:

1. *X* and *Y* extent. The output from

```
ogrinfo -ro -so Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2.shp \
Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2
```

can be piped through awk to obtain the extents:

```
ogrinfo -ro -so Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2.shp \
Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2 | awk '/Extent: /'
```

The xmin, ymin, and xmax, ymax values will need to be put into variables:

```
xmin=236141.010000
ymin=3763743.940000
xmax=236824.920000
ymax=3764111.850000
```

2. *Number of rows and columns.* We also define the number of rows and columns for a 1m DEM by calculating xmax-xmin and ymax-ymin.

```
ncols=684
nrows=368
```

3. *Defining the interpolation method.* `gdal_grid` allows several interpolation methods and we experiment with two: linear interpolation and inverse distance weighted (IDW). We define:

```
linear="linear:radius1=2:radius2=3:angle=0.0:nodata=-9999"
```

For IDW, we use a specific implementation that relies on nearest neighbor searching with an efficient way of defining a maximum number of neighbor points to be used. Both examples set nodata/NaN to -9999:

```
idw="invdistnn:radius=2.0:max_points=50:min_points=1:nodata=-9999"
```

4. *Interpolating to a grid.* We use the option `GDAL_NUM_THREADS ALL_CPUS` to use all available cores for the interpolation.

```
gdal_grid --config GDAL_NUM_THREADS ALL_CPUS -of GTiff -co PREDICTOR=3 -co \
COMPRESS=DEFLATE -co ZLEVEL=7 -ot Float32 -txe $xmin $xmax -tye $ymin $ymax \
-zfield Z -a $linear -outsize $ncols $nrows -a_srs epsg:26911 \
Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2.shp \
dtm_interp/Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2_linear_1m.tif
```

and

```
gdal_grid -of GTiff -co PREDICTOR=3 -co COMPRESS=DEFLATE -co ZLEVEL=7 -ot Float32 -txe \
$xmin $xmax -tye $ymin $ymax -zfield Z -a $idw -outsize $ncols $nrows -a_srs \
epsg:26911 Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2.shp \
dtm_interp/Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2_idw_1m.tif
```

5. Clip and warp interpolated GeoTIFF. The interpolation will result in border artifacts that will need to be clipped. We use the shapefile Pozo_DTM_noveg_UTM11_NAD83_cat16.shp. Second, we inteprolate the grid to a 1m grid spacing and make sure that the grid is aligned with integer UTM coordinates -*tap*.

```
gdalwarp -tap -tr 1 1 -r bilinear --config GDAL_NUM_THREADS ALL_CPUS -co PREDICTOR=3 \
-co COMPRESS=DEFLATE -co ZLEVEL=7 -t_srs epsg:26911 -srcnodata -9999 -dstnodata \
-9999 -ot Float32 -crop_to_cutline -cutline Pozo_DTM_noveg_UTM11_NAD83_cat16.shp \
dtm_interp/Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2_linear_1m.tif \
dtm_interp/Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2_linear_1m_clip.tif
```

and

```
gdalwarp -tap -tr 1 1 -r bilinear --config GDAL_NUM_THREADS ALL_CPUS -co PREDICTOR=3 \
-co COMPRESS=DEFLATE -co ZLEVEL=7 -t_srs epsg:26911 -srcnodata -9999 -dstnodata \
-9999 -ot Float32 -crop_to_cutline -cutline Pozo_DTM_noveg_UTM11_NAD83_cat16.shp \
dtm_interp/Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2_idw_1m.tif \
dtm_interp/Pozo_USGS_UTM11_NAD83_cat16_smrf_cl2_idw_1m_clip.tif
```

The interpolated output tifs show differences: The IDW interpolation provides the closest results to the *blast2dem* approach, especially in the steeper areas (Figure 8).

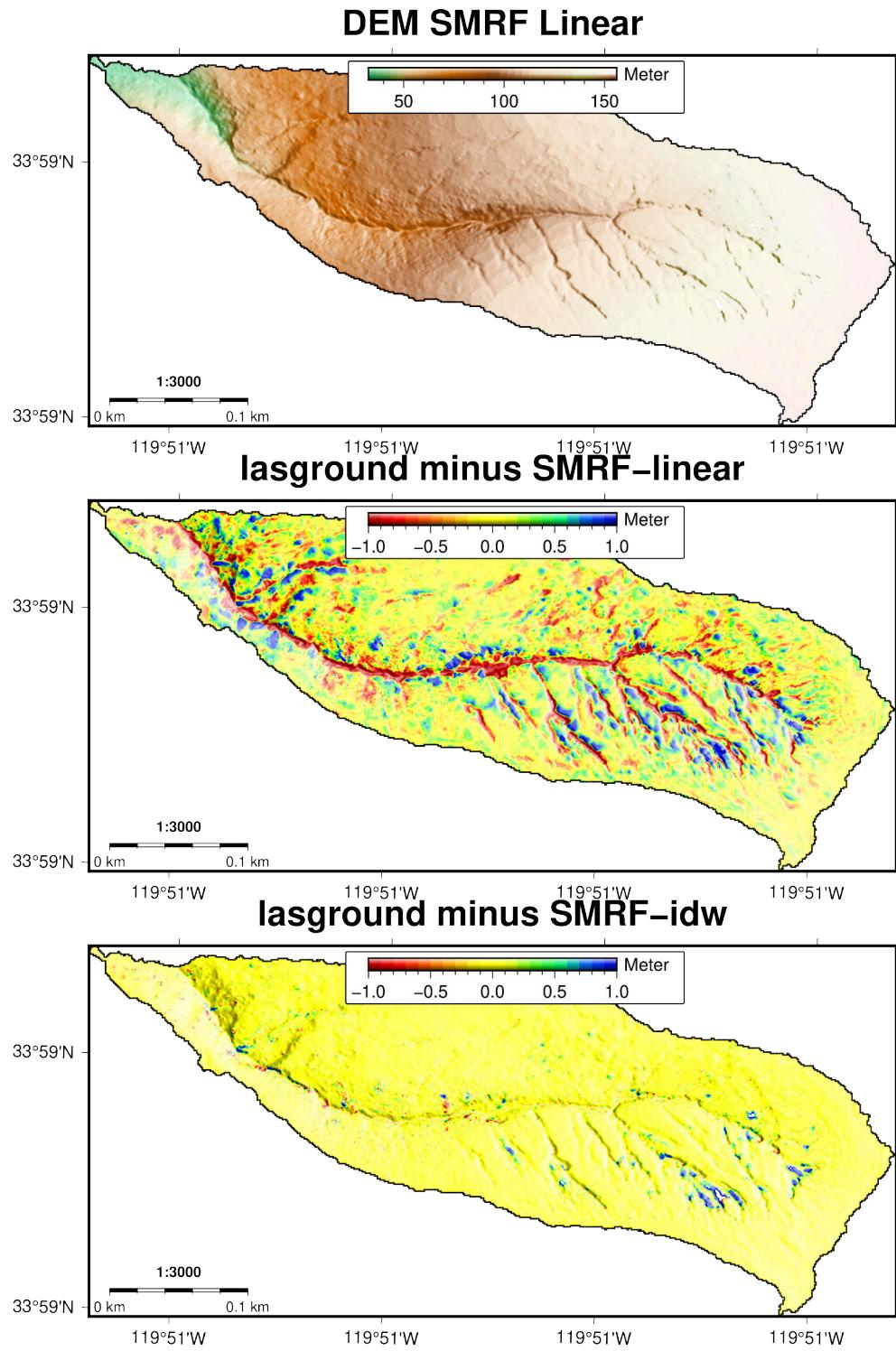


Figure 8: Map view of the PDAL DTM, generated from SMRF classification. Middle row shows linearly interpolated ground-classified points and bottom row shows IDW interpolation. Both grids have been compared to the adjusted lasground grid that has been used as a comparison in Figure 4). See [GMT bash script](#) for generating this figure.

3.3 Interpolation to a grid: points2grid

This method is implemented by PDAL's [writers.gdal](#) approach. [Points2Grid](#). You can use the source code to run the interpolation to a grid from a ground-classified PC from the command line with `points2grid`.

3.4 Classifying ground points with lidar2dem

See `l2d_classify -h`. Not implemented yet.

4 Point Cloud (PC) Subsampling

Subsampling of PCs can be applied for some ground-classified PCs that are very dense and noisy. In some cases, we may just want to get initial results very fast - using fewer points will help to do that.

4.1 PC Decimation and filtering with PDAL

PDAL provides some [culling](#) filters that can be directly applied on the classified PC (or also on the raw, unclassified PC). Most notably are [Poisson Subsampling](#), [Decimation](#), and [Voxelgrids](#).

Applying a [Poisson Subsampling](#) to the lasground-classified PC with a minimum distance between the points of 0.25m can be achieved with the pipeline `example01_Possion_sampling.json`:

```
{
  "pipeline": [
    {
      "type": "readers.las",
      "filename": "Pozo_USGS_UTM11_NAD83_cat16_clg_cl2.laz"
    },
    {
      "type": "filters.sample",
      "radius": 0.5
    },
    {
      "type": "writers.las",
      "filename": "Pozo_USGS_UTM11_NAD83_cat16_clg_cl2_radius50cm.las"
    }
  ]
}
```

Then run this with:

```
pdal pipeline example01_Possion_sampling.json
```

The Poisson sub sampled (filtered) PC has been decimated, but the PC's structure has been maintained (Figure 9).



Figure 9: Oblique view of a subste of the lasground-classified PC. Colors are taken from draped airphoto. Top view shows original PC (ground-class only), middle shows a Poisson radius of 10cm (minimum distance 10cm), bottom shows a radius of 50cm.

Decimation can be carried out with the following pipeline *example01_decimation_sampling.json*:

```
{  
  "pipeline": [  
    {  
      "type": "readers.las",  
      "filename": "Pozo_USGS_UTM11_NAD83_cat16_clg_cl2.laz"  
    },  
    {  
      "type": "filters.decimation",  
      "step": 10  
    },  
    {  
      "type": "writers.las",  
      "filename": "Pozo_USGS_UTM11_NAD83_cat16_clg_cl2_step10.las"  
    }  
  ]  
}
```

Then run this with:

```
pdal pipeline --nostream example01_Possion_sampling.json
```

5 Point Cloud (PC) Geomorphologic roughness calculation and topographic detrending

Detrending Point Cloud (PC) data with slope and calculating topographic roughness and curvature from PCs.

The code reads in a ground-classified PC from a LAS/LAZ file and calculates several geomorphology-relevant metrics on the PC. Input files can be from a lidar or a Structure-from-Motion (SfM) PC, but should be ground classified (for descriptions on how to ground-classify your data, see previous sections). You may also want to subsample your point cloud to generate a more homogenous point cloud. However, we provide a PC density-based subsampling method that homogenizes the PC density by either giving a fraction (or percentage) of points to be used (e.g., 0.8) or the number of neighborhood points for 1m grid spacing.

The algorithm allows defining a radius which is used to fit a linear plane through the point cloud to detrend the data (i.e., normalize the point cloud with mean elevation of 0). These data are used to calculate deviations from the mean (roughness) and identify rills, arroyos, incised canyons, and other

forms of erosion processes. By varying the radius over which the plane is fitted, several scales of the landscape can be analyzed (similar to varying radii of topographic relief). The algorithm chooses seed points from the PC with a user-defined spacing (for example 1m) and calculated statistics for each seed point with that given radius.

Output includes a set of shapefile and geotiffs that show statistics of the PC within the given radius. Also, CSV and H5 files are created that contain lists of seed point location and statistical results for further analysis in Python or Matlab.

The code is parallelized using *multiprocess* and uses by default all available cores. This significantly speeds up statistic calculation of the point cloud. For large point clouds, a significant amount of RAM is required or you will need to split your point cloud into smaller tiles.

The code performs several additional steps that are described in detail below. In summary, these are:

1. Finding seed points with a given spacing, usually 1m to 5m. The seed points are aligned to integer coordinates (e.g., UTM).
2. For each seed point and its neighborhood (for 1m spacing of seed points, points within a radius of 0.5m are used), statistics are calculated from the PC (and all points). These include, for example, slope, curvature, variability of height (Z) and slope-normalized Z values (for a full list and detailed description see below). The parameters also allow detrending the points within the seed-point radius by its slope and derive surface-roughness parameters not influenced by terrain slope.
3. Two algorithms included allows to subsample a point cloud either by a max. number of neighborhood points (e.g., k=5) or by defining a fraction of points to use to create a point cloud with approximately similar point-cloud density based on probabilities. The subsampled point cloud is written as a new LAS file. This step of point-cloud homogenization can also be performed by other approaches (see for example [PDAL filters](#). Especially, the filter [Poisson Subsampling](#), [Voxelcenternearestneighbor](#), and [Voxelcentroidnearestneighbor](#) are interesting.
4. The code interpolates the seed points to a grid and writes the output as a geotiff. In addition, LAS files with seed points with relevant metrics are created.
5. If GMT is installed (and that option has been selected when running from the command line), a set of output maps is generated for initial visualization.

5.1 Input Parameters and options

NOTE: pc_geomorph_roughness relies on a PC containing only ground points.

Before running, make sure the proper environment is activated:

```
source activate PC_py3
```

List of argument is obtained by

```
python ~/PC_geomorph_roughness/pc_geomorph_roughness.py
```

and an extended help for each parameters is obtained by

```
python ~/PC_geomorph_roughness/pc_geomorph_roughness.py -h
```

With explanation of input parameters in:

```
usage: pc_geomorph_roughness.py [-h] -i INLAS [--raster_m RASTER_M]
                                 [--raster_m_range RASTER_M_RANGE]
                                 [--subsample_1m_pc_k SUBSAMPLE_1M_PC_K]
                                 [--subsample_1m_pc_p SUBSAMPLE_1M_PC_P]
                                 [--redo_subsample_1m_pc_p REDO_SUBSAMPLE_1M_PC_P]
                                 [--k_nr_of_neighbors K_NR_OF_NEIGHBORS]
                                 [--dem_fname DEM_FNAME]
                                 [--shapefile_clip SHAPEFILE_CLIP]
                                 [--epsg_code EPSG_CODE]
                                 [--create_shapefiles CREATE_SHAPEFILES]
                                 [--create_geotiff CREATE_GEOTIFF]
                                 [--create_gmt CREATE_GMT]
                                 [--create_las CREATE_LAS]
                                 [--mean_z_only MEAN_Z_ONLY]
                                 [--nr_of_cores NR_OF_CORES]
                                 [--max_nr_of_neighbors_kdtree MAX_NR_OF_NEIGHBORS_KDTREE]
                                 [--pt_lower_threshold PT_LOWER_THRESHOLD]
                                 [--create_gmt_maps CREATE_GMT_MAPS]
                                 [--gmt_title GMT_TITLE]
                                 [--gmt_basename GMT_BASENAME]
                                 [--plot_plane_fits PLOT_PLANE_FITS]
                                 [--plot_plane_fits_nr_points PLOT_PLANE_FITS_NR_POINTS]
                                 [--ransac_on RANSAC_ON]
```

PointCloud (PC) processing **for** DEM statistics. Deriving gridded ground data
(elevation and slope) using centroid coordinates. B. Bookhagen
(bodo.bookhagen@uni-potsdam.de), V0.2 Dec 2018.

optional arguments:

-h, --help	show this help message and exit
-i INLAS, --inlas INLAS	LAS/LAZ file with point-cloud data. This file must only contain ground points (class == 2)

```

--raster_m RASTER_M   Raster spacing or diameter for subsampling seed points
                      on LAS/LAZ PC. Usually 0.5 to 10 m, default = 1. Seed
                      points are selected from radii half this diameter.
--raster_m_range RASTER_M_RANGE
                      Raster spacing for subsampling seed points on LAS/LAZ
                      PC. Uses a list of ranges with spacing, e.g.,
                      --raster_m_range "1 10 1" will create raster files
                      with spatial resolutions of 1 to 10 m in 1 m steps.
--subsample_1m_pc_k SUBSAMPLE_1M_PC_K
                      Number of points in radius=0.5m that are randomly
                      subsampled from the full point cloud. This is useful
                      if point-cloud density greatly varies, because
                      statistics calculated for seed points with different
                      point numbers may be biased. If subsample_pc_k > 0
                      then the point cloud will be homogenized by selecting
                      k=n neighbors for each 1-m seed point. For example, if
                      subsample_pc_k 10, then each 1m seed point will have
                      only 10 neighbors. Subsampled point cloud is written
                      to LAS file.
--subsample_1m_pc_p SUBSAMPLE_1M_PC_P
                      Factor to subsample point cloud based on probability.
                      If --subsample_1m_pc_p 0.8, a point cloud with 80% of
                      the input points is generated and sampling of point
                      cloud is based on density probability. That is,
                      neighboring points for a seed point with a high number
                      of neighbors a sampled less often, than a seed point
                      with fewer neighbors. Will use original points, but
                      creates a reduced point cloud. Calculates probability
                      from 1m seed-point spacing. Subsampled point cloud is
                      written to LAS file.
--redo_subsample_1m_pc_p REDO_SUBSAMPLE_1M_PC_P
                      Flag to redo random subsampling based on probability.
                      By default, an existing file with a probability is
                      loaded, if you set "--redo_subsample_1m_pc_p true",
                      the random subsampling based on probability will be
                      rerun and stored in a separate LAS file.
--k_nr_of_neighbors K_NR_OF_NEIGHBORS
                      Number of neighbors for dynamic density estimation
                      (k_nr_of_neighbors = 50 by default). Change to lower
                      number for lower-density point clouds to increase
                      processing speed. For SfM PCs this should be set to 100
                      or higher.
--dem_fname DEM_FNAME

```

Filename of DEM to extract point spacing. Used to identify seed-point coordinates. Useful **if** a DEM exists and one wants to create point-cloud statistics aligned to the DEM grid.

--shapefile_clip SHAPEFILE_CLIP
 Name of shapefile to be used to clip interpolated surfaces. Make sure to give full pathname. This is likely the shapefile that has been previously generated to subset/clip the point-cloud data.

--epsg_code EPSG_CODE
 EPSG code (integer) to define projection information. This should be the same EPSG code as the input LAS data (no re-projection is included in **this** code yet) and can be taken from LAS/LAZ input file. Add **this** to ensure that output shapefile and GeoTIFFs are properly geocoded.

--create_shapefiles CREATE_SHAPEFILES
 Create point shapefiles in UTM (see --epsg_code) and Geographic-DD projection. These contain all attributes calculated during the processing (**default** no shapefiles are created: --create_shapefiles 0, set to --create_shapefiles 1 to generate shapefiles).

--create_geotiff CREATE_GEOTIFF
 Create interpolated geotif files from PC data (**default** no: --create_geotiff 0, set to --create_geotiff 1 to generate geotiff files). Note that creating geotiff files may increase processing time

--create_gmt CREATE_GMT
 Create gmt point or vector files **for** plotting with GMT shapefiles in UTM (see --epsg_code) and Geographic-DD projection. These contain all attributes calculated during the processing (**default** no: --create_gmt 0, set to --create_gmt 1 to generate GMT files).

--create_las CREATE_LAS
 Create LAS point file from seed points. The color shows mean elevation of the seed points (**default** no: --create_las 0, set to --create_las 1 to generate LAS files).

--mean_z_only MEAN_Z_ONLY
 Calculate mean elevation **for** grid cell size and no other parameters.

--nr_of_cores NR_OF_CORES
 Max. number of cores to use **for** multi-core processing.

Default is to use all cores (`--nr_of_cores 0`), set to `--nr_of_cores 6` to use 6 cores. For some memory-intensive applications, it may be useful to reduce the number of cores.

`--max_nr_of_neighbors_kdtree MAX_NR_OF_NEIGHBORS_KDTREE`
 Setting the max. number of neighbors **for** KDTree search. This can remain at 100 points **for** airborne lidar data. For example, **if** you have a point density of 5 pts/m², 100 pts are 20 m². You may want to consider increasing **this** when using terrestrial lidar data, SfM data, or airborne data with high point densities.

`--pt_lower_threshold PT_LOWER_THRESHOLD`
 Minimum number of points **for** performing plane fitting and slope normalization (lower point threshold). If there are less than `pt_lower_threshold` in the seed-point neighborhood (**default** `--pt_lower_threshold 3`), a point fitting is not performed and values are set to NaN.

`--create_gmt_maps CREATE_GMT_MAPS`
 BASH File with GMT commands **for** plotting maps. Full path and filename is required. Will need to be fine tuned (see example).

`--gmt_title GMT_TITLE`
 GMT title to appear in output map.

`--gmt_basename GMT_BASENAME`
 GMT basename **for** Postscript filenames.

`--plot_plane_fits PLOT_PLANE_FITS`
 Create plots of plane fits **for** individual seed points with more than `plot_plane_fits_nr_points` (**default** = 10) neighborhood points in subdirectory "maps". Mostly **for** testing purposes, **default** is off (`--plot_plane_fits 0`).

`--plot_plane_fits_nr_points PLOT_PLANE_FITS_NR_POINTS`
 Set number of neighborhood points to create plot **for** seed point. Default is `--plot_plane_fits_nr_points 10`. You will need to adjust **this** **for** larger neighborhood radii.

`--ransac_on RANSAC_ON`
 Turn RANSAC fitting on. This will significantly increase the processing time, but will give better and tighter fits.

5.2 Output Files

The folder *HDF* contains all results in HDF format. The same results are also stored in CSV format. Both can be readily loaded by post-processing software (Python, Matlab, R). The following fields are stored:

- *1SeedX, 2SeedY, 3SeedZ*: contain the seed-point location (this is a real point in the PC)
- *4MeanX, 5MeanY, 6MeanZ*: contain the average of all X, Y, Z points for the seed point calculated by taking the average of each coordinate. This results in an interpolated point
- *7Z_min, 8Z_max*: minimum and maximum Z (height) for this seed point
- *9Dz_max, 10Dz_min, 11Dz_std*: values are obtained from slope-normalized points. All points within a seed-point radius were normalized by their slope (i.e., a fitted plane has been subtracted from all points and their mean elevation is now 0). These fields contain maximum, minimum, and standard deviation of the normalized PC.
- *12Dz_range, 13Dz_9010p, 14Dz_7525p, 15Dz_var*: Additional metrics derived from the slope-normalized PC: range (max. - min.), 90th minus 10th percentile, 75th minus 25 th percentile (IQR: InterQuartileRange), variance
- *16Slp_p1*: Linear (polynomial order=1) least-squared fit
- *17Slp_p1r*: RMSE in meter from linear (polynomial order=1) least-squared fit
- *18Slp_p2*: Second order polynomial (polynomial order=2) least-squared fit
- *19Slp_p2r*: RMSE in meter of second-order polynomial (polynomial order=2) least-squared fit
- *20Nr_lidar*: number of lidar points in the seed-point neighborhood, will increase with larger radii.
- *21CC_p2, 22CT_p2, 23CP_p2*: Contour Curvature, tangential Curvature, and profile Curvature derived from fitting the second-order polynom.
- *24CC_p4, 25CT_p4, 26CP_p4*: Contour Curvature, tangential Curvature, and profile Curvature derived from fitting the fourth-order polynom.
- *27C_p4r*: RMSE in meter of fourth-order polynomial (polynomial order=4) least-squared fit
- *28StdZ*: Standard deviation of elevations in seed-point neighborhood (not slope-normalized).

5.2.1 GeoTIFF files

There are several interpolated results onto equally-spaced grids in the *geotiff* folder. These can be used for visualization in QGIS or GMT. See map outputs below REFERENCE.

5.2.2 LAS files

The results of the seed-point analysis are also written to las files (*LAS* directory). These are colored by their respective variables (Figure 11). Currently, the following parameters are created and colored by different colormaps:

- *_xyzmean.las: Mean position of X, Y, Z seed points, colored by elevation
- *_iqrDZ.las: IQR of normalized elevation (roughness indicator)
- *_slope_p1_lstsq.las: Linear (polynomial order = 1) least-square fits of planar slope
- *_slope_p2_lstsq.las: Second order (polynomial order = 2) least-square fits of planar slope
- *_radius_mean_curv.las: Second order (polynomial order = 2) least-square fits of curvature

6 Examples

In the following three sections, we provide detailed step-by-step explanation of the processing with *PC_geomorph_roughness*. There are GMT scripts included that generate output maps. We focus on three sub-catchments in the SW part of Santa Cruz Island (Pozo catchment) 6.4. All data are available through [OpenTopography](#), but a subset of the data is provided in the respective subdirectories.

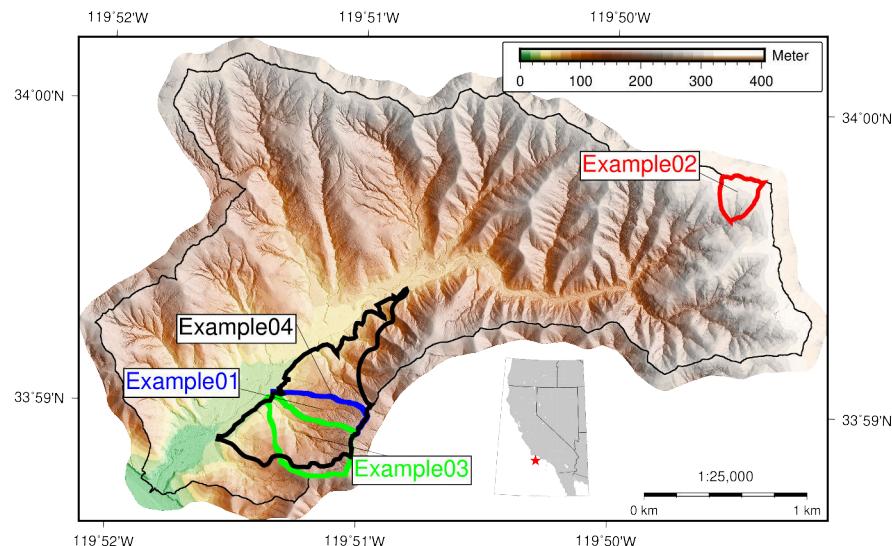


Figure 10: Topographic overview map of the southwestern part of Santa Cruz Island (Pozo catchment). The four example catchments discussed are outlined by polygons (see [GMT bash script](#)) for creating this map.

6.1 Example 01 - subcatchment of the SW area of Pozo on SCI

In order to show how *PC_geomorph_roughness* works, we show the usual steps done to process a catchment.

NOTE: If you re-run PC_geomorph_roughness with different options, make sure to remove the directories or files containing the data. By default, PC_geomorph_roughness will load existing HDF5 and geotiff files. For example, do a rm -fr hdf/ geotiff/ LAS/ pickle/

6.1.1 Summary of pre-processing steps to create a classified point cloud

In order to generate a ground-classified point cloud, we use the following script and approach:

```
cd example_01
pdal translate Pozo_USGS_UTM11_NAD83_cat16.laz \
    Pozo_USGS_UTM11_NAD83_cat16_SMRF_cl2.las --json example01_PDAL_SMRF_pipeline.json
```

Next, generate a DTM from the ground-classified PC:

```
mkdir dtm_interp
pdal pipeline --nostream example01_writers_gdal_smrf_Zmean_1m.json
```

6.1.2 First steps: random subsampling

Following steps are necessary to process the SMRF-classified PC (-i *Pozo_USGS_UTM11_NAD83_cat16_SMRF_cl2.las*) with smoothing ranging from 1 to 10 m in steps of 1 m (-raster_m_range "1 10 1"), clipping the interpolated surface with a shapefile outlining the catchment (-shapefile_clip *Pozo_DTM_noveg_UTM11_NAD83_cat16.shp*), assigning the proper EPSG code to the output GeoTIFF file (-epsg_code 26911), using all available cores for statistical calculation (-nr_of_cores 0), creating output GeoTIFF files (-create_geotiff 1), not creating GMT masp (-create_gmt 0), not creating shapefiles (-create_shapefiles 0), but creating a LAS file with mean elevation (-create_las 1), and subsampling the pointcloud with k=10 neighbors (-subsample_1m_pc_k 10). In order to keep track of the output, we pipe the text output to a log file. Because some python numpy operations may produce warnings (for example, if there are not enough points in a grid cell), we turn off these warnings with -W ignore:

```
python -W ignore ~/Dropbox/soft/github/PC_geomorph_roughness/pc_geomorph_roughness.py \
    -i Pozo_USGS_UTM11_NAD83_cat16_SMRF_cl2.las \
    --raster_m_range "1 10 1" \
    --shapefile_clip Pozo_DTM_noveg_UTM11_NAD83_cat16.shp \
    --epsg_code 26911 --nr_of_cores 0 --create_geotiff 1 --create_gmt 0 \
    --create_shapefiles 0 --create_las 1 --subsample_1m_pc_k 10 > log.txt
```

```
--create_shapefiles 0 --create_las 1 \
--subsample_1m_pc_k 10 \
2>&1 | tee \
Pozo_USGS_UTM11_NAD83_cat16_SMRF_cl2_pc_geomorph_roughness_subsample_k10_1_10_1.log
```

Use displaz to view the randomly subsampled point cloud with k=5 neighbors (displaz Pozo_USGS_UTM11_NAD83_cat16_SMRF_cl2_randomsubsampled_k10.las). The directory LAS contains the seed-point outputs at the requested spacings: The file *LAS/Pozo_USGS_UTM11_NAD83_cat16_SMRF_cl2_seed_pts_1.00m_radius_xyzmean.las* contains seed-point spacing of 1m and the mean X, Y, Z values in color. Interesting LAS files to explore are, for example, *LAS/Pozo_USGS_UTM11_NAD83_cat16_SMRF_cl2_seed_pts_2.00m_radius_slope_p1_lstsq.las* that show the least-squared fit of the slope derived from all points in a 2m neighborhood (r=1m).

We investigate the mean height, least-squared slope and IQR of normalized elevation in the LAS directory (Figures 11 and 12):

- *Pozo_USGS_UTM11_NAD83_cat16_SMRF_cl2_seed_pts_1.00m_radius_xyzmean.las*
- *Pozo_USGS_UTM11_NAD83_cat16_SMRF_cl2_seed_pts_1.00m_radius_slope_p1_lstsq.las*
- *Pozo_USGS_UTM11_NAD83_cat16_SMRF_cl2_seed_pts_1.00m_radius_slope_p2_lstsq.las*
- *Pozo_USGS_UTM11_NAD83_cat16_SMRF_cl2_seed_pts_1.00m_radius_iqrZ.las*

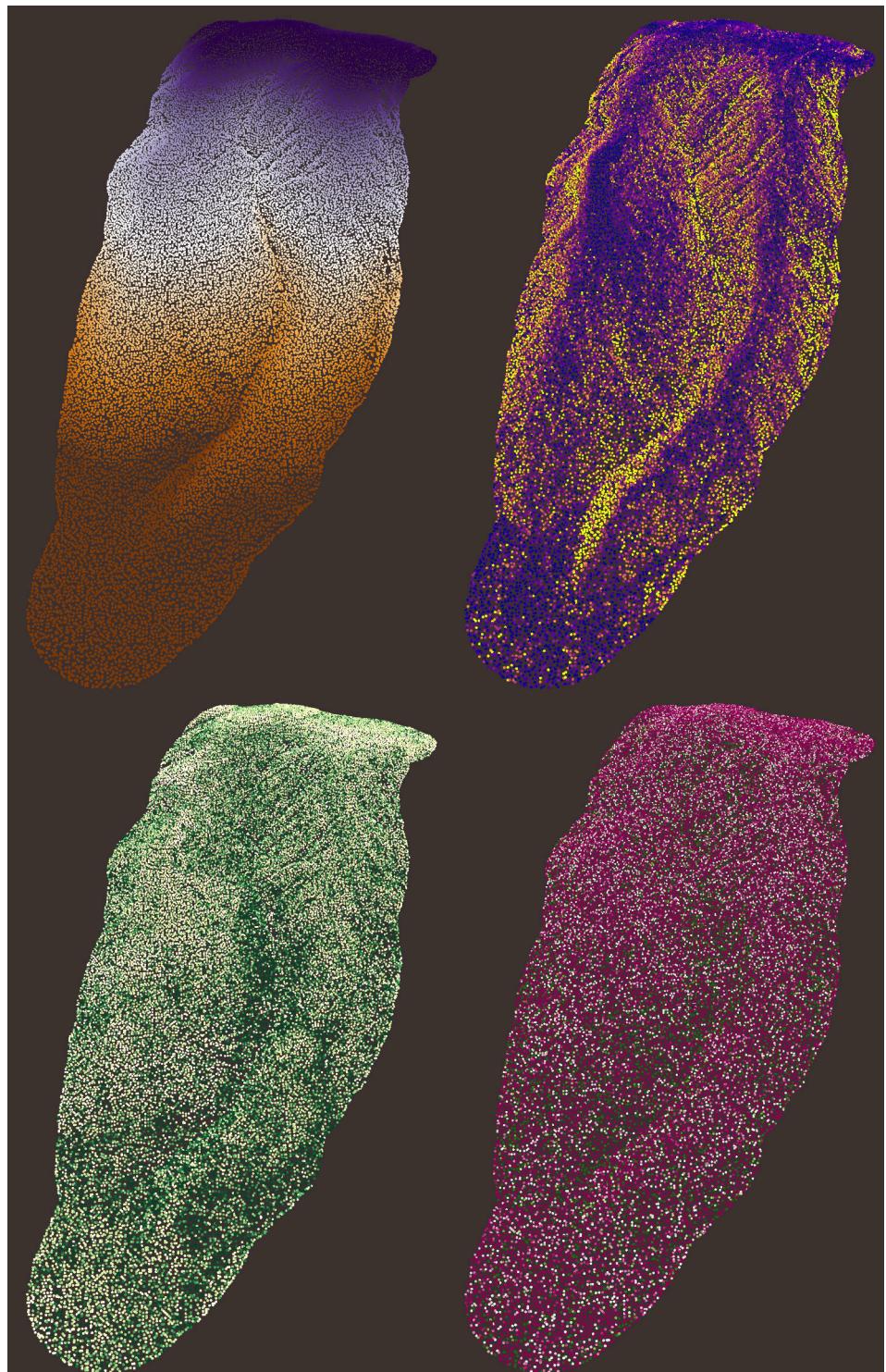


Figure 11: Oblique view of a PC showing mean elevation for each seed point (top left), least-squared slope (top right), IQR of normalized elevation (bottom left), and curvature (bottom right).

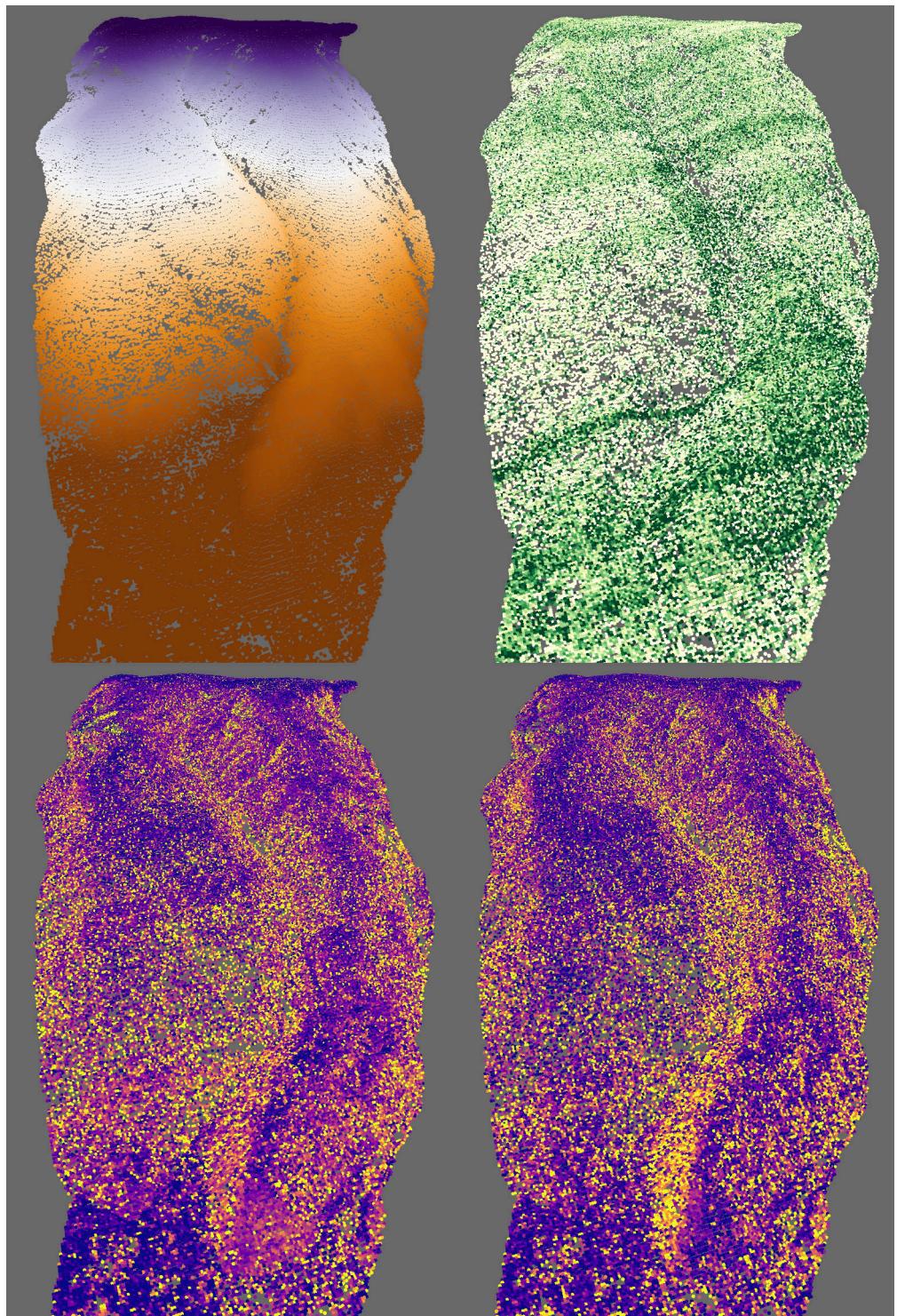


Figure 12: Alternative oblique view of a PC showing mean elevation for each seed point (top left), IQR of normalized elevation (top right), least-squared linear (polynom order=1) slope (bottom left), least-squared linear (polynom order=2) slope (bottom right).

6.1.3 What polynomial fit is most appropriate?

The code fits a polynom to all points in the neighborhood. It uses a least-squared approach to reduce the impact of outliers. For polynom order=1 (planar fit), the results are shown as a point cloud in Figure 12-bottom left. We can compare the fits for some example point. In most cases, the least-squared planar (order=1) fit for slope determination works just fine (see Figures 16 to 16. The curvature calculation is based on the mean curvature of the second-order polynom.

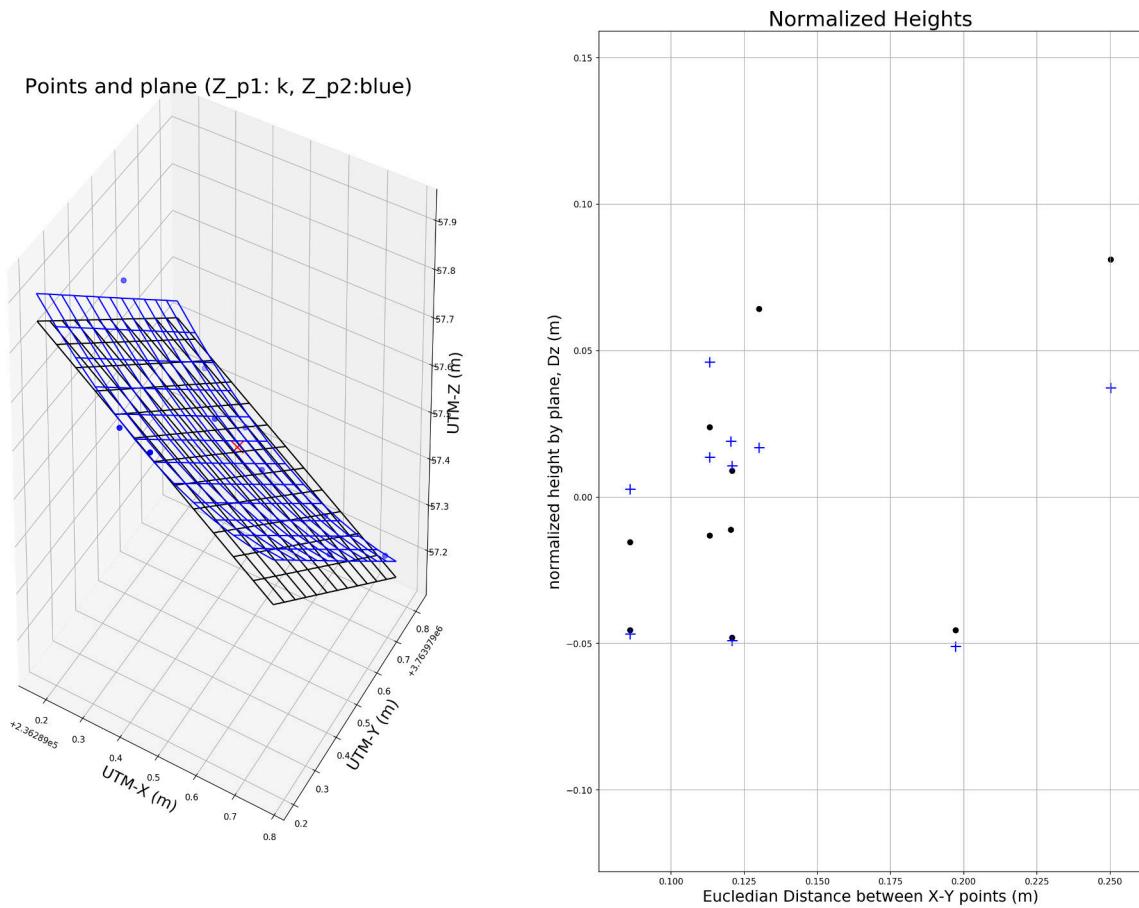


Figure 13: Characteristic example where planar (order=1) fit in black colors is very close to a polynomial fit with order=2 in blue color. Orginial points are blue dots. Right plot shows normalized point heights and their distances: black dots are distances for the planar fit, blue points for the polynomial order=2 fit.

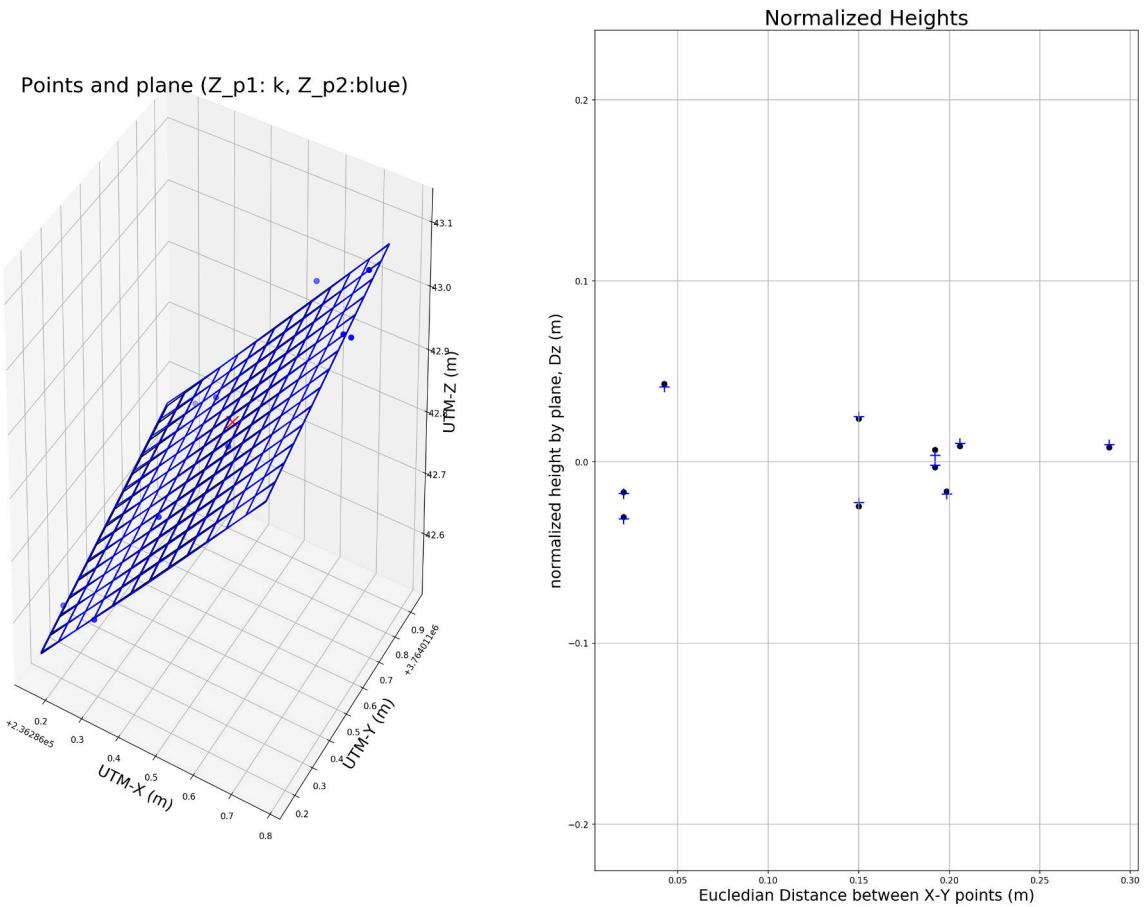


Figure 14: Characteristic example where planar (order=1) fit in black colors is very close to a polynomial fit with order=2 in blue color. Original points are blue dots. Right plot shows normalized point heights and their distances: black dots are distances for the planar fit, blue points for the polynomial order=2 fit.

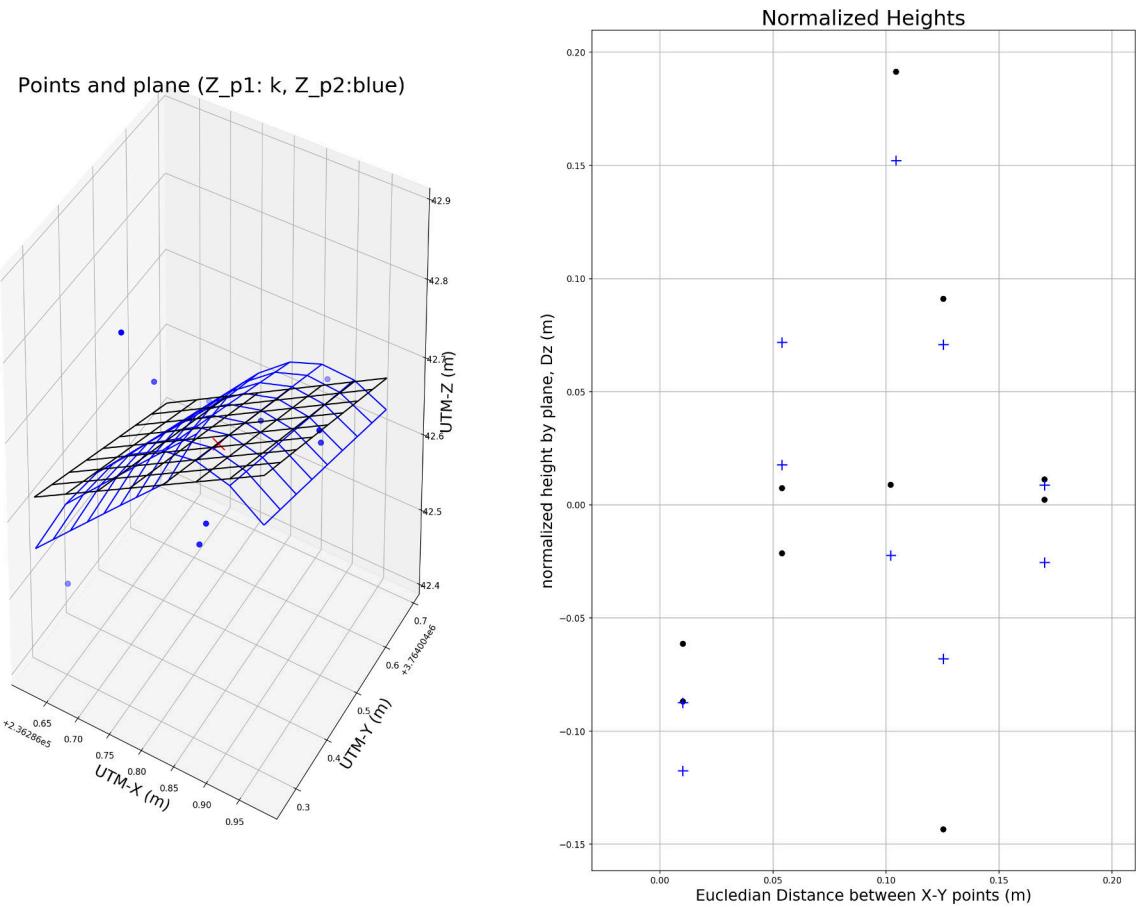


Figure 15: Characteristic example where planar (order=1) fit in black colors is different to a polynomial fit with order=2 in blue color. Original points are blue dots. Right plot shows normalized point heights and their distances: black dots are distances for the planar fit, blue points for the polynomial order=2 fit.

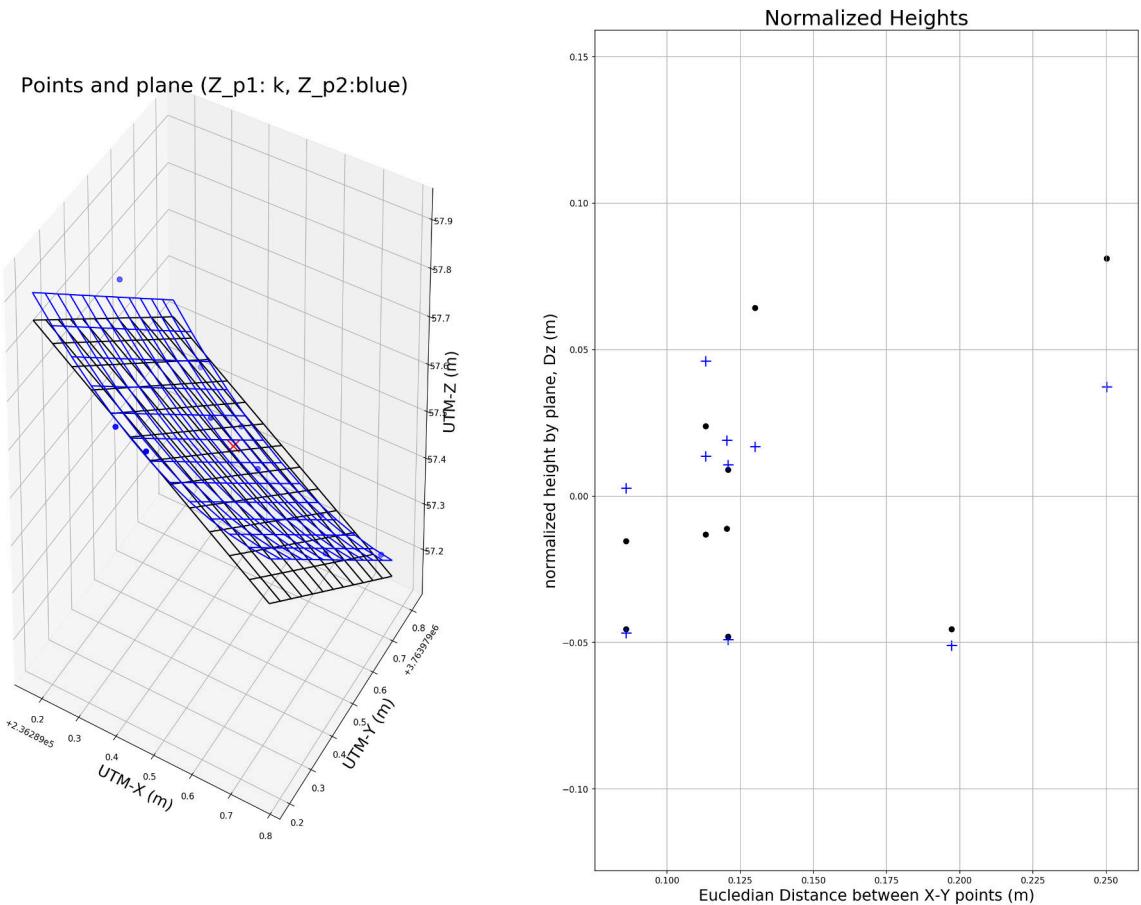


Figure 16: Characteristic example where planar (order=1) fit in black colors is very close to a polynomial fit with order=2 in blue color. Original points are blue dots. Right plot shows normalized point heights and their distances: black dots are distances for the planar fit, blue points for the polynomial order=2 fit.

6.1.4 Next steps: density-based subsampling

*NOTE: If you re-run PC_geomorph_roughness with different options, make sure to remove the directories or files containing the data. By default, PC_geomorph_roughness will load existing HDF5 and geotiff files. Save or move your results to a different folder and remove folders. For example, do a **rm -fr hdf/ geotiff/ LAS/ pickle/***

In addition to the above example, we now subsample the pointcloud to 80% of the original points by PC density. Note the option `-subsample_1m_pc_p 0.8`.

```
python -W ignore ~/Dropbox/soft/github/PC_geomorph_roughness/pc_geomorph_roughness.py \
-i Pozo_USGS_UTM11_NAD83_cat16_SMRF_cl2.las \
```

```
--raster_m_range "1 10 1" \
--shapefile_clip Pozo_DTM_noveg_UTM11_NAD83_cat16.shp \
--epsg_code 26911 --nr_of_cores 0 --create_geotiff 1 --create_gmt 0 \
--create_shapefiles 0 --create_las 1 \
--subsample_1m_pc_p 0.8 \
2>&1 | tee \
Pozo_USGS_UTM11_NAD83_cat16_SMRF_cl2_pc_geomorph_roughness_subsample_p08_1_10_1.log
```

6.1.5 Next steps: density-based subsampling and GMT map generation

In addition to the above example, we now subsample the pointcloud to 80% of the original points by PC density and we generate GMT output files. Note the options `-create_gmt_maps`, `-gmt_title`, and `-gmt_basename`.

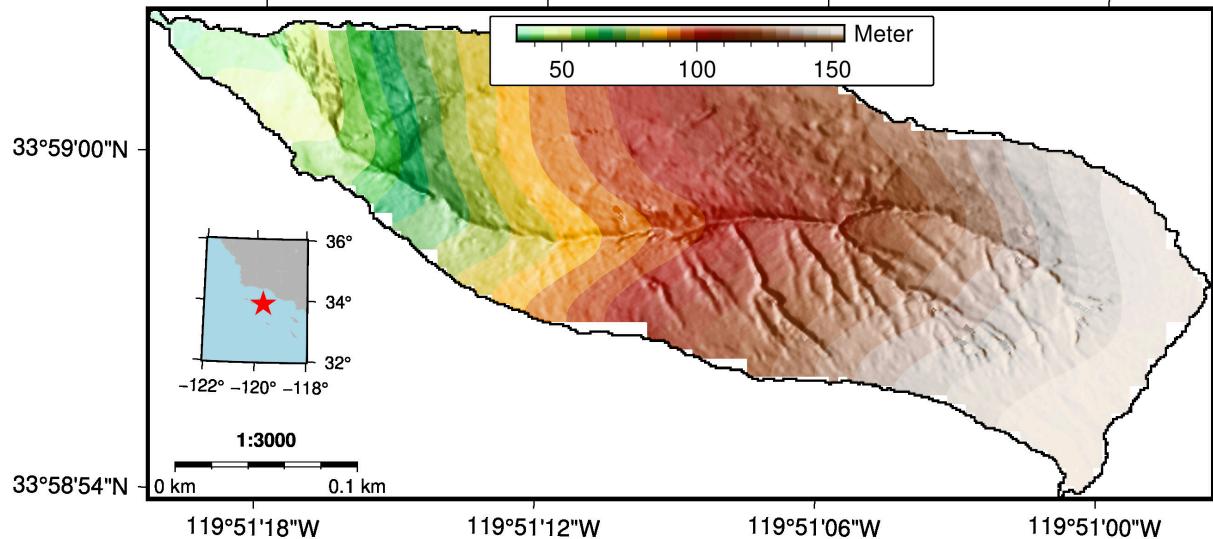
Before maps can be generated with GMT, the GMT script will need to be edited. See `PC_geomorph_roughness/NEED_TO_EDIT.gmt` as a starting point. For the directory `example_01`, we include a GMT script that will generate a useful set of maps (see `example_01/example01_create_map_view_of_PC_geomorph_output_gmt.sh`). The script is a bash script that calls GMT to generate several maps. You will need to set scale and other parameters for your catchment.

NOTE: Make sure to give the full path to the Shapefile used as clip and for the GMT Shell script!

```
python -W ignore ~/github/PC_geomorph_roughness/\
PC_geomorph_roughness/pc_geomorph_roughness.py \
-i Pozo_USGS_UTM11_NAD83_cat16_SMRF_cl2.las \
--raster_m_range "1 10 1" \
--shapefile_clip ~/github/PC_geomorph_roughness/\
example_01/Pozo_DTM_noveg_UTM11_NAD83_cat16.shp \
--epsg_code 26911 --nr_of_cores 0 --create_geotiff 1 --create_gmt 0 \
--create_shapefiles 0 --create_las 1 \
--subsample_1m_pc_p 0.8 \
--create_gmt_maps ~/github/PC_geomorph_roughness/\
example_01/example01_create_map_view_of_PC_geomorph_output_gmt.sh \
--gmt_title "Ex01 in Pozo" \
--gmt_basename "Example01_cl2" \
2>&1 | tee \
Pozo_USGS_UTM11_NAD83_cat16_SMRF_cl2_pc_geomorph_roughness_subsample_p08_1_10_1.log
```

This will generate a set of output maps with GMT that are illustrated below (Figures 17, 18, 19, 20, 21, ??, 23, ??, ??, ??, ??).

"Ex01 SMRF 1.0m" interpolated DEM



"Ex01 SMRF 1.0m" Delta DEM

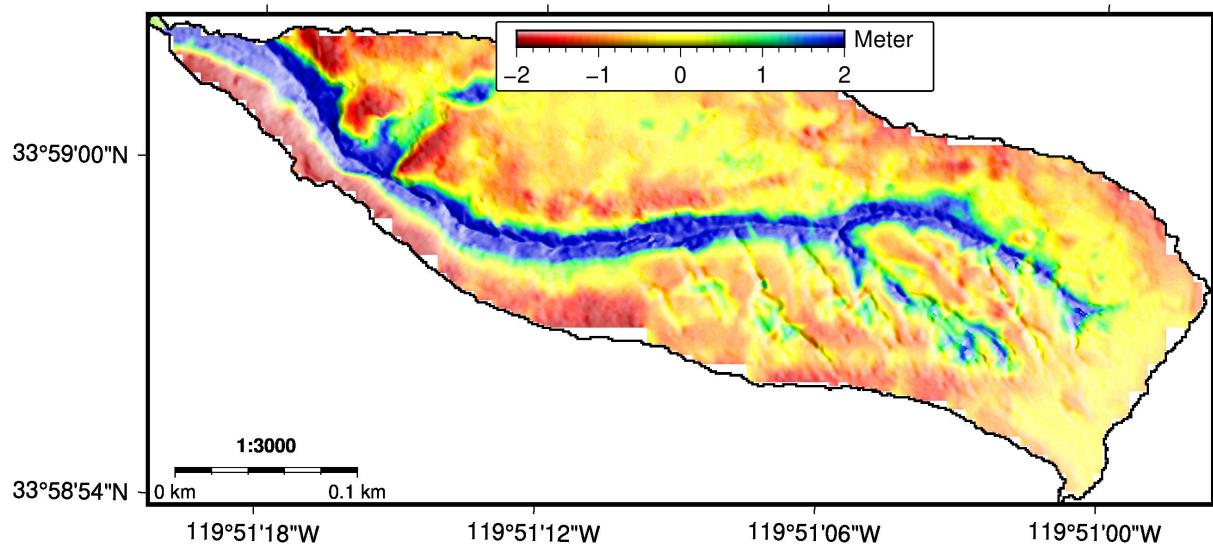
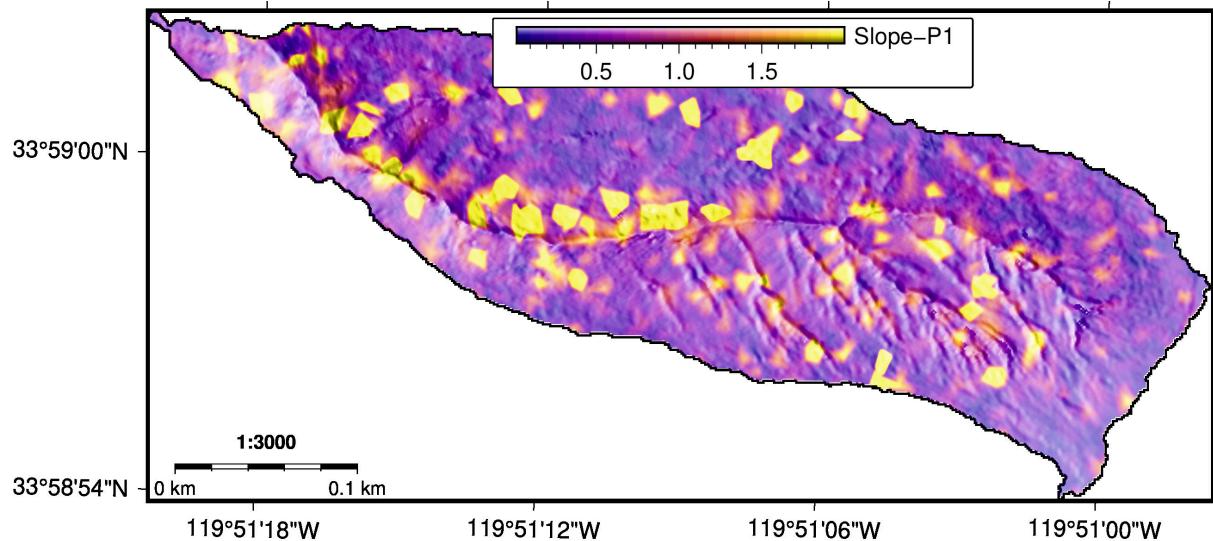


Figure 17: Output of 1m DEM generated from the interpolated point cloud and difference DEM between the mean seed height and the interpolated DEM. Note that the interpolated DEM is based on all ground points, while the mean-seed point DEM used the largely reduced seed point PC.

"Ex01 SMRF 1.0m" Slope-P1 from PC



"Ex01 SMRF 1.0m" Slope-P2 from PC

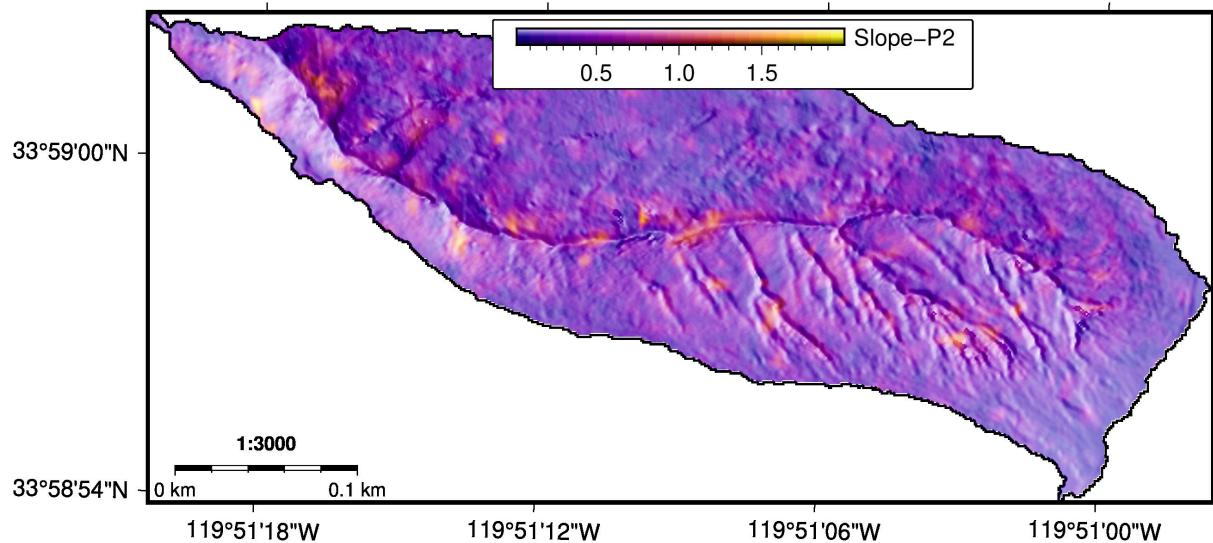
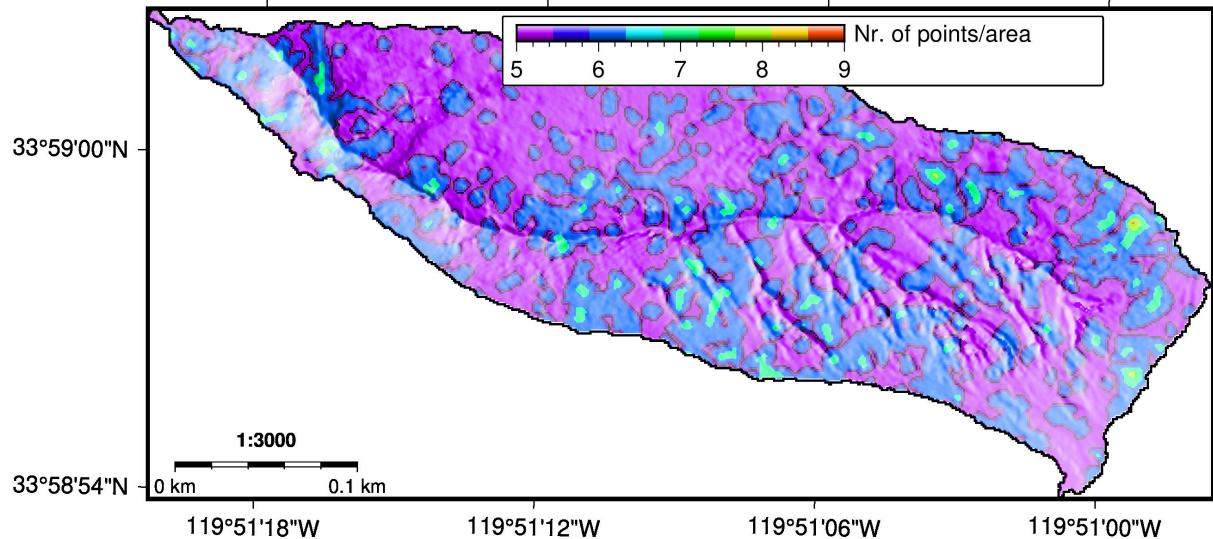


Figure 18: Output of the slope values derived for each seed points and using the seed-point neighbors. The second-order polynomial fit usually provides more realist results for natural (steep) terrain. Note that for some areas, slopes are steep because of few points leading to low fit quality (large residual, cf 21).

"Ex01 SMRF 1.0m" Nr. Lidar Points/area



"Ex01 SMRF 1.0m" Dz standard deviation

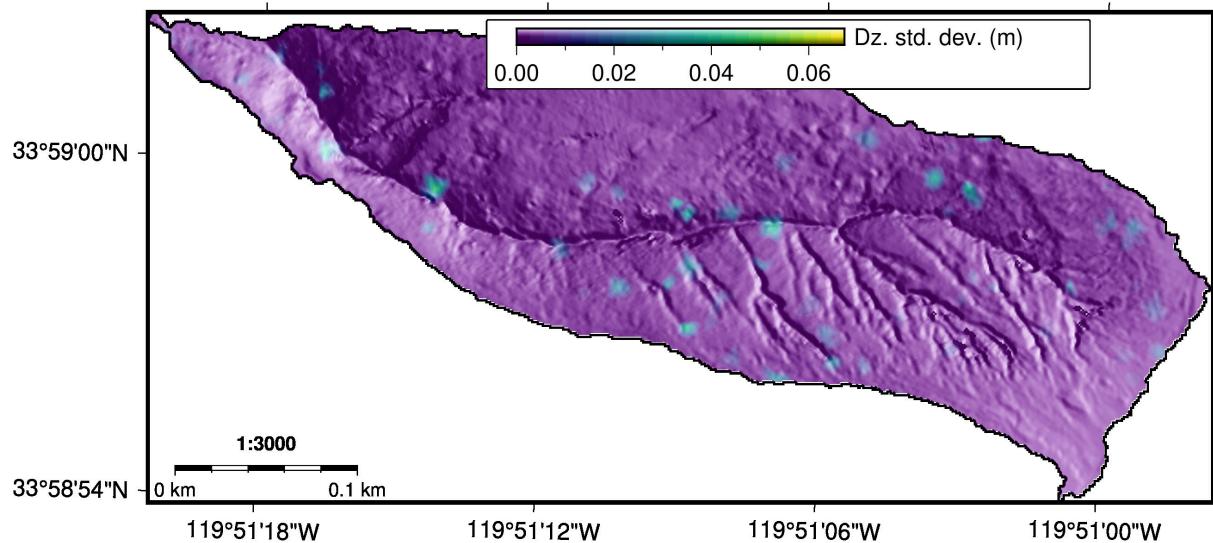
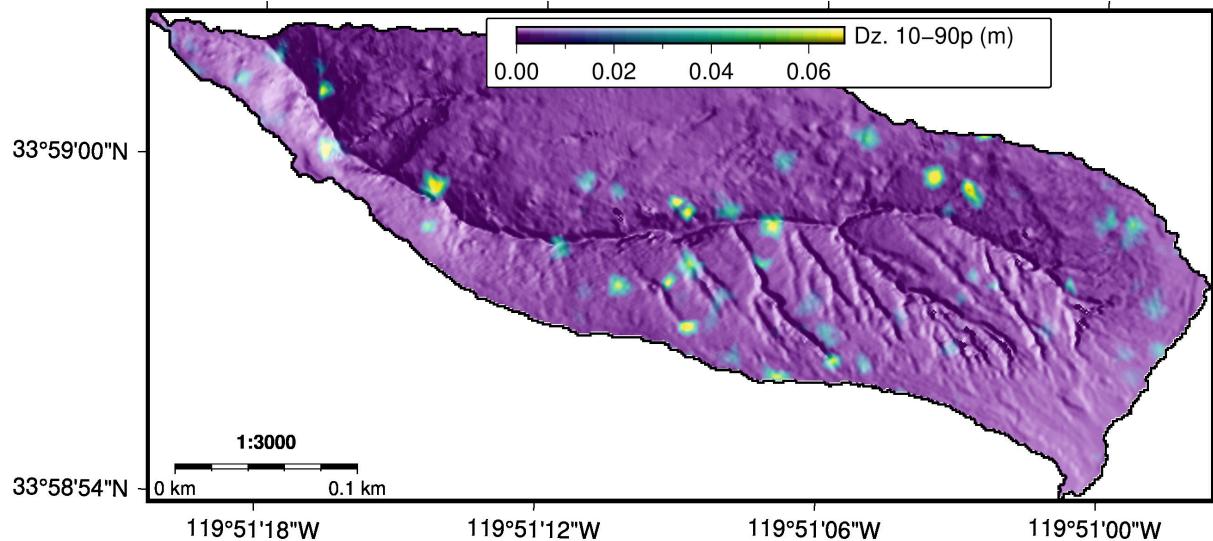


Figure 19: Output of number of points for seed-point neighborhood and the standard deviation of normalized points (normalized by slopes). The higher the standard deviation, the more rough the terrain.

"Ex01 SMRF 1.0m" Dz Range 10th–90th perc.



"Ex01 SMRF 1.0m" Dz IQR

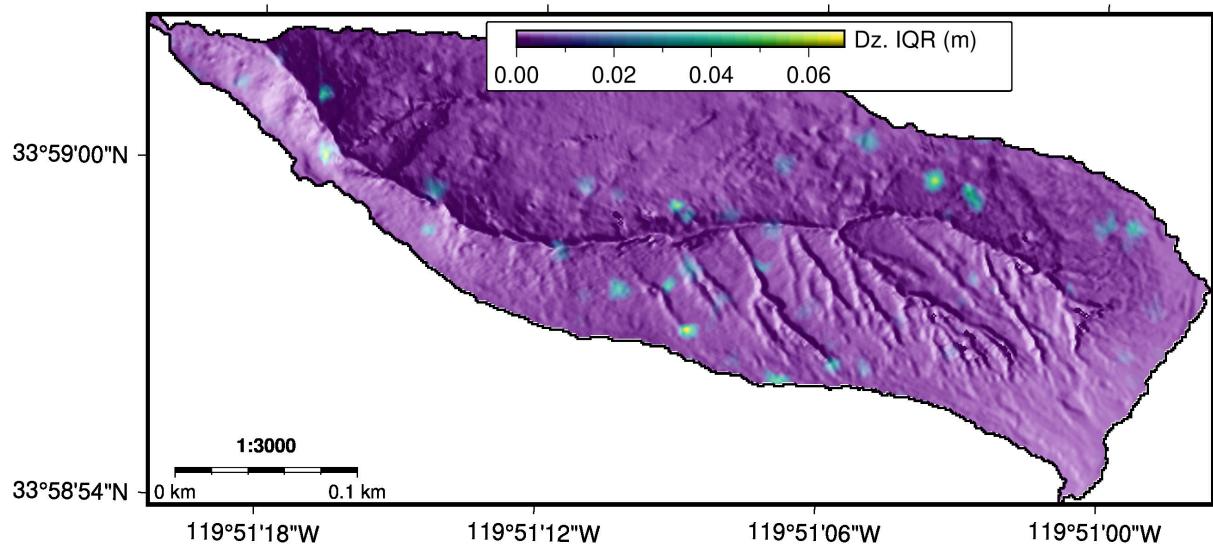
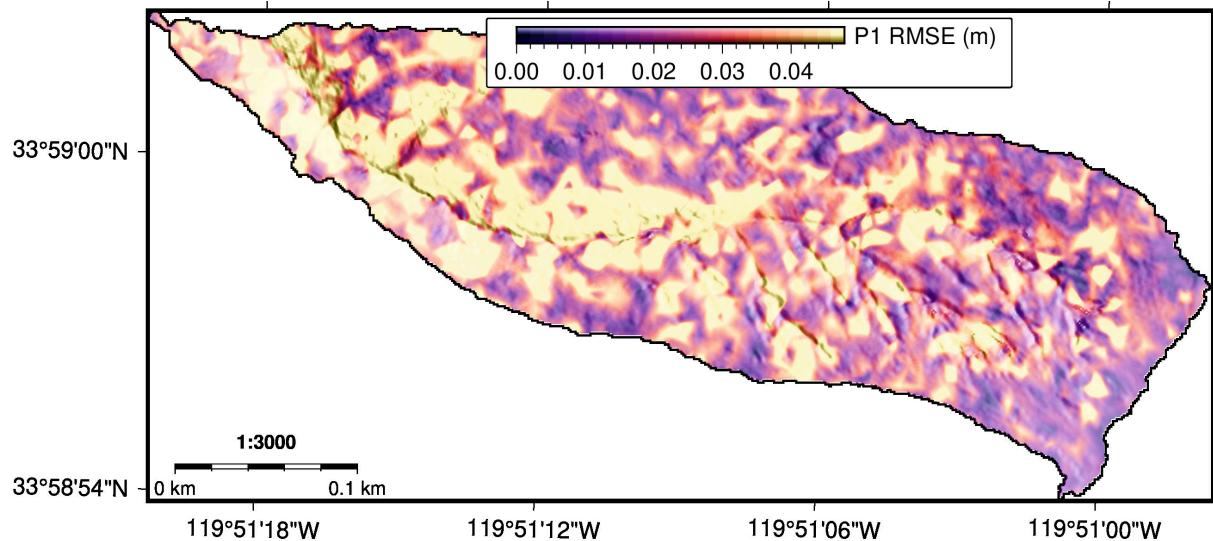


Figure 20: Results from slope-normalized roughness calculations: 90th minus 10th percentile and inter-quartil range (IQR: 75th-25th percentile)

"Ex01 SMRF 1.0m" P1 RMSE from PC



"Ex01 SMRF 1.0m" P2 RMSE from PC

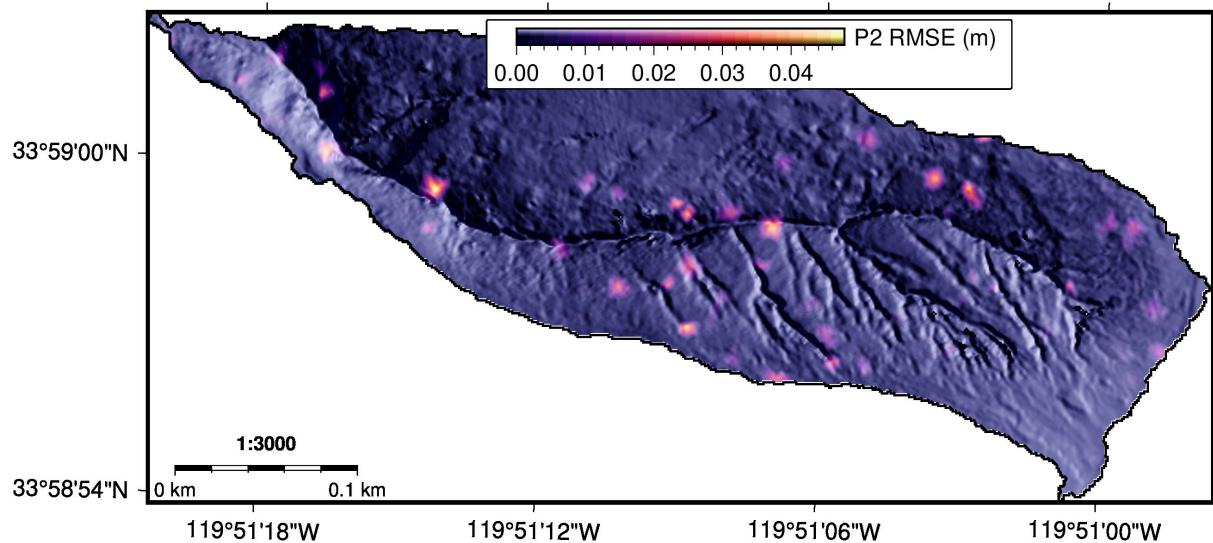


Figure 21: RMSE (in meter) from the first and second order polynomial fitting.

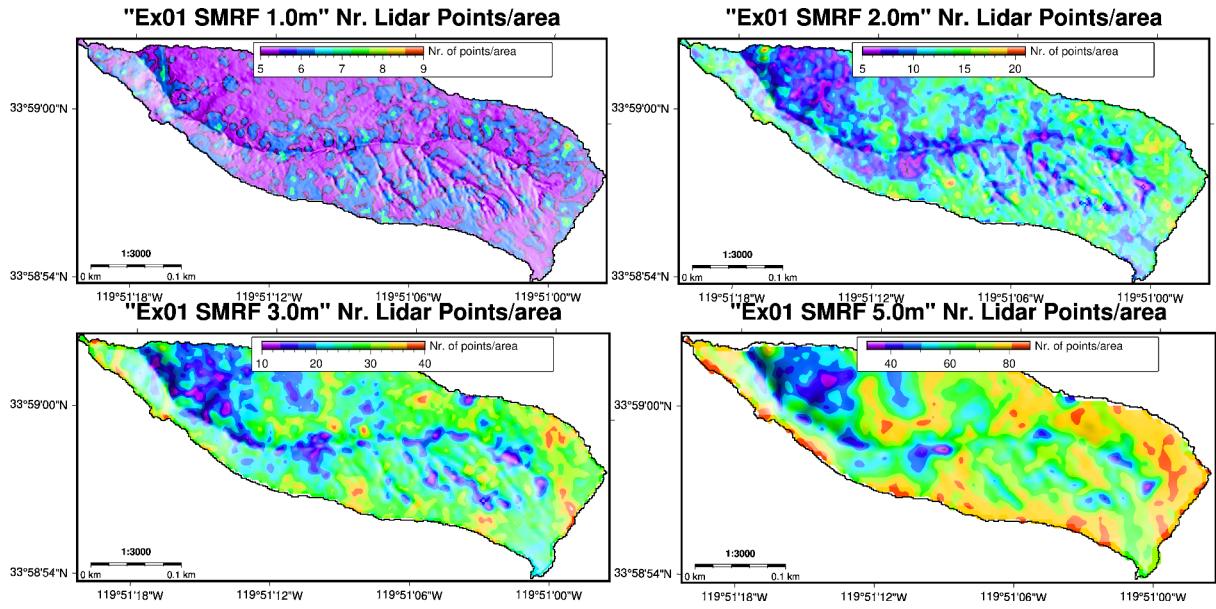


Figure 22: Number of points in analysis radii increase rapidly and will lead to more robust results. Here, the number of neighborhood points for 1, 2, 3, and 5 m of interpolation diameters are shown. Note the different ranges of the colorscale

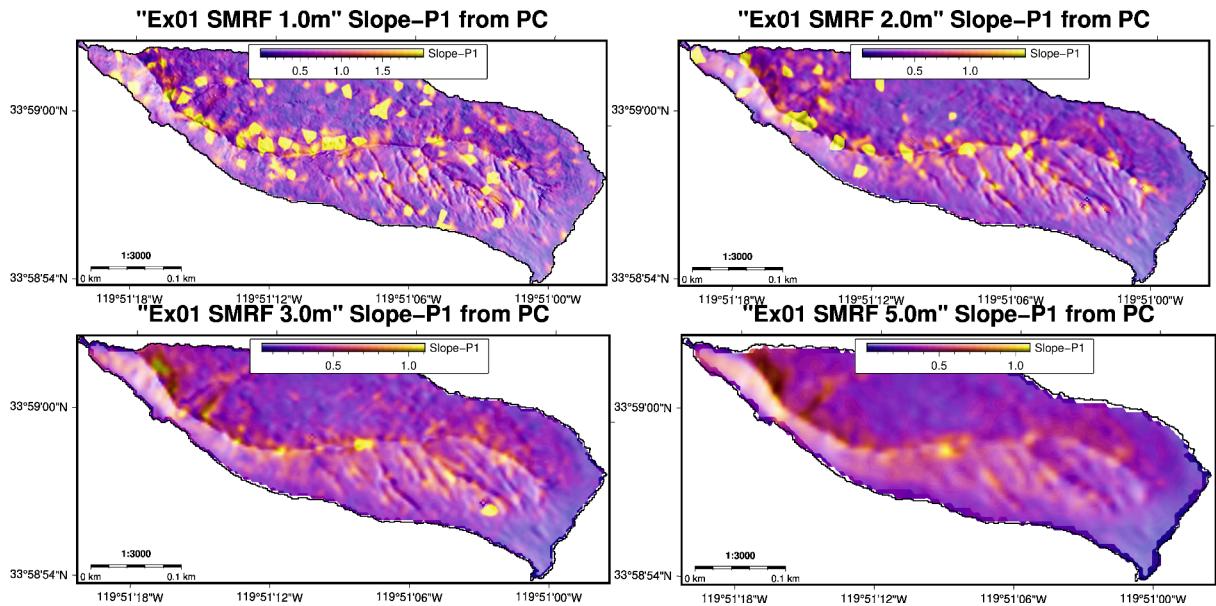


Figure 23: Deriving slopes for large neighborhood of points results in more realistic slope values. Here, the slopes for diameters of 1, 2, 3, and 5 m are shown. We only show the planar (polynomial order=1) slopes.

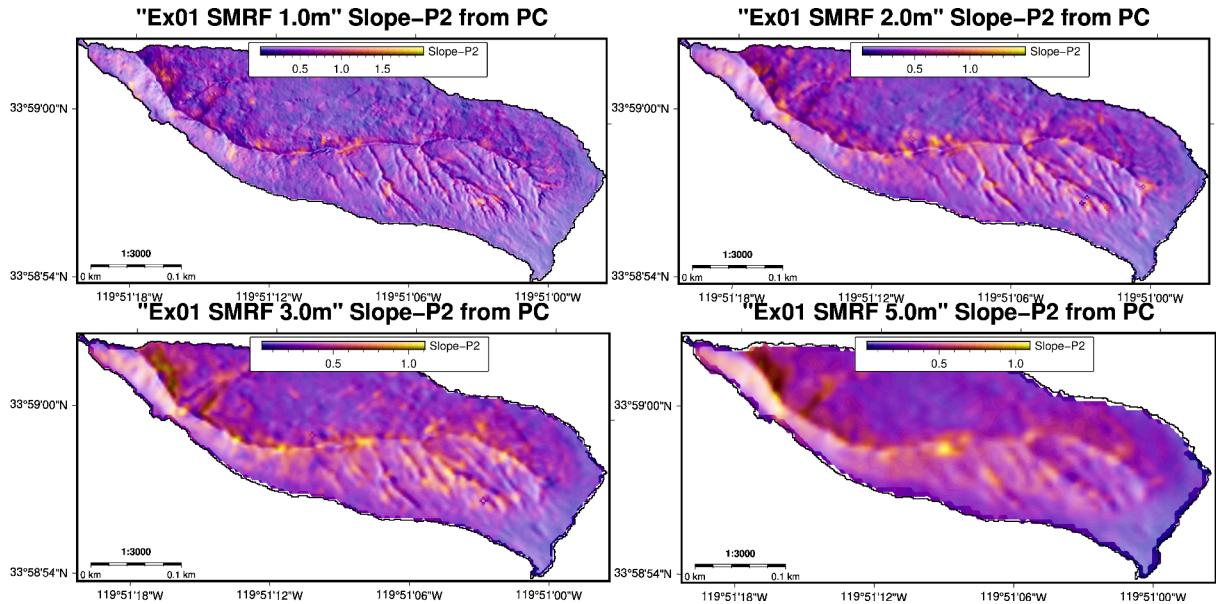


Figure 24: Deriving slopes for large neighborhood of points results in more realistic slope values. Here, the slopes for diameters of 1, 2, 3, and 5 m are shown. We only show the second order polynomials (polynomial order=2) slopes. These have generally a lower RMSE than polynomial orders=1.

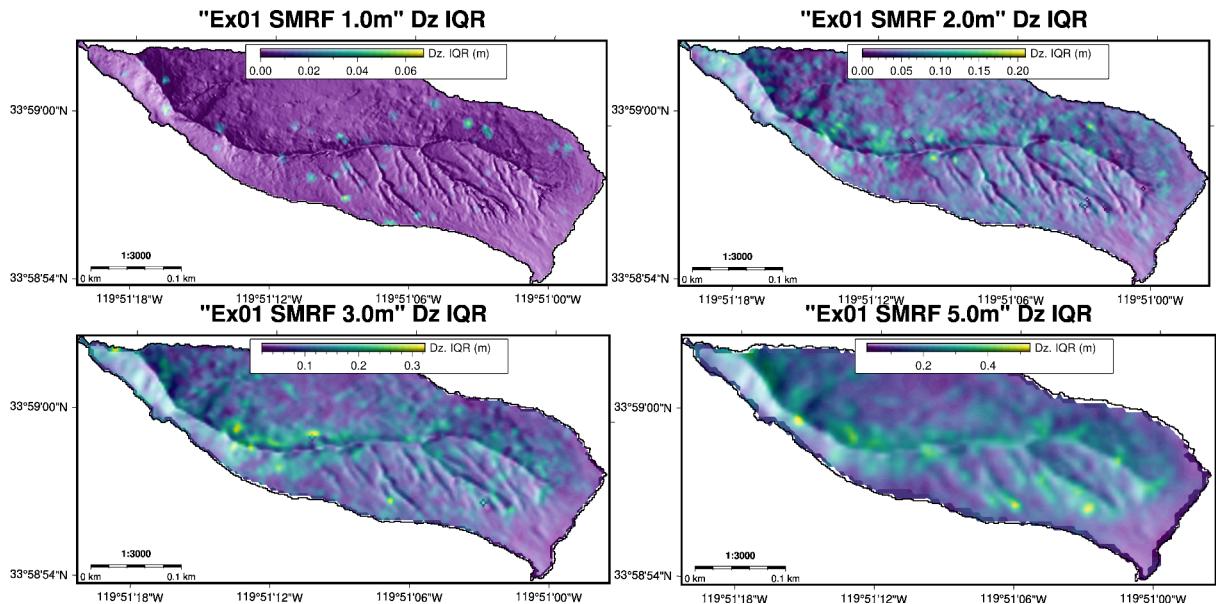


Figure 25: The IQR reflects channels and arroyos with increasing interpolation radii. Here, the slope-normalized elevation (IQR) for 1, 2, 3, and 5 m of interpolation diameters are shown.

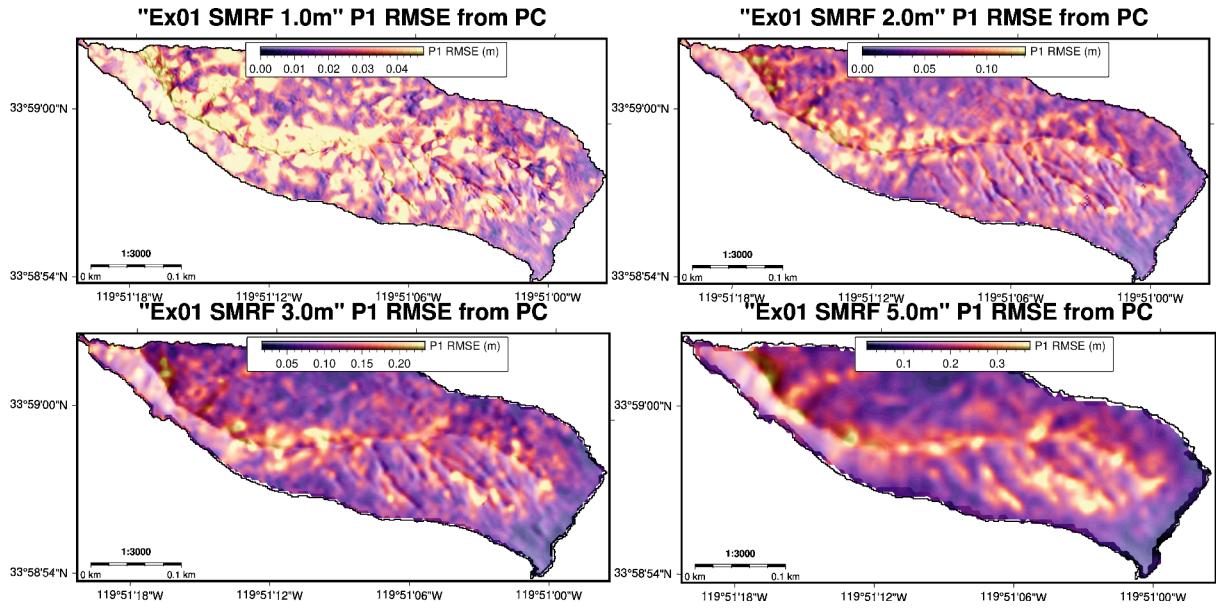


Figure 26: RMSE (m) from linear fits (polynomial order = 1) for radii 1, 2, 3, and 5 m are shown.

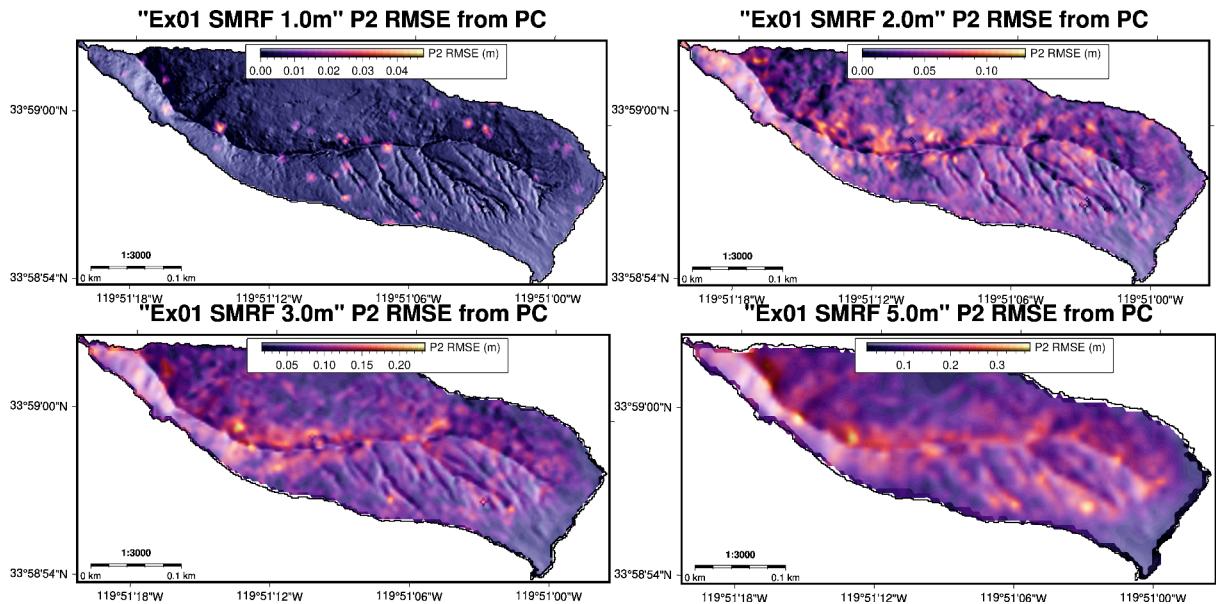


Figure 27: RMSE (m) from linear fits (polynomial order = 2) for radii 1, 2, 3, and 5 m are shown.

6.1.6 Analysis of the lasground classified PC

In a separate approach, we have used the lasground-classified PC to illustrate the differences for the PDAL-SMRF classified PC. This file is also provided on the github page ([exam-](#)

ple_01/Pozo_USGS_UTM11_NAD83_cat16_clg_cl2.laz).

We first save previous results:

```
mv geotiff geotiff_PDAL_SMRF  
mv LAS LAS_PDAL_SMRF  
mv vrt vrt_PDAL_SMRF  
mv hdf hdf_PDAL_SMRF
```

Then we run *PC_geomorph_roughness* for the lasground-classified PC:

```
python -W ignore ~/github/PC_geomorph_roughness/\\  
PC_geomorph_roughness/pc_geomorph_roughness.py \\  
-i Pozo_USGS_UTM11_NAD83_cat16_clg_cl2.laz \\  
--raster_m_range "1 10 1" \\  
--shapefile_clip ~/github/PC_geomorph_roughness/\\  
example_01/Pozo_DTM_noveg_UTM11_NAD83_cat16.shp \\  
--epsg_code 26911 --nr_of_cores 0 --create_geotiff 1 --create_gmt 0 \\  
--create_shapefiles 0 --create_las 1 \\  
--subsample_1m_pc_p 0.8 \\  
--create_gmt_maps ~/github/PC_geomorph_roughness/\\  
example_01/example01_create_map_view_of_PC_geomorph_output_gmt.sh \\  
--gmt_title "Ex01 in Pozo" \\  
--gmt_basename "Example01_cl2" \\  
2>&1 | tee \\  
Pozo_USGS_UTM11_NAD83_cat16_lasground_cl2_pc_geomorph_roughness_subsample_p08_1_10_1.log
```

The results are similar to the PDAL-SMRF classified PC (Figures 28, ??, ??, 31, and 32).

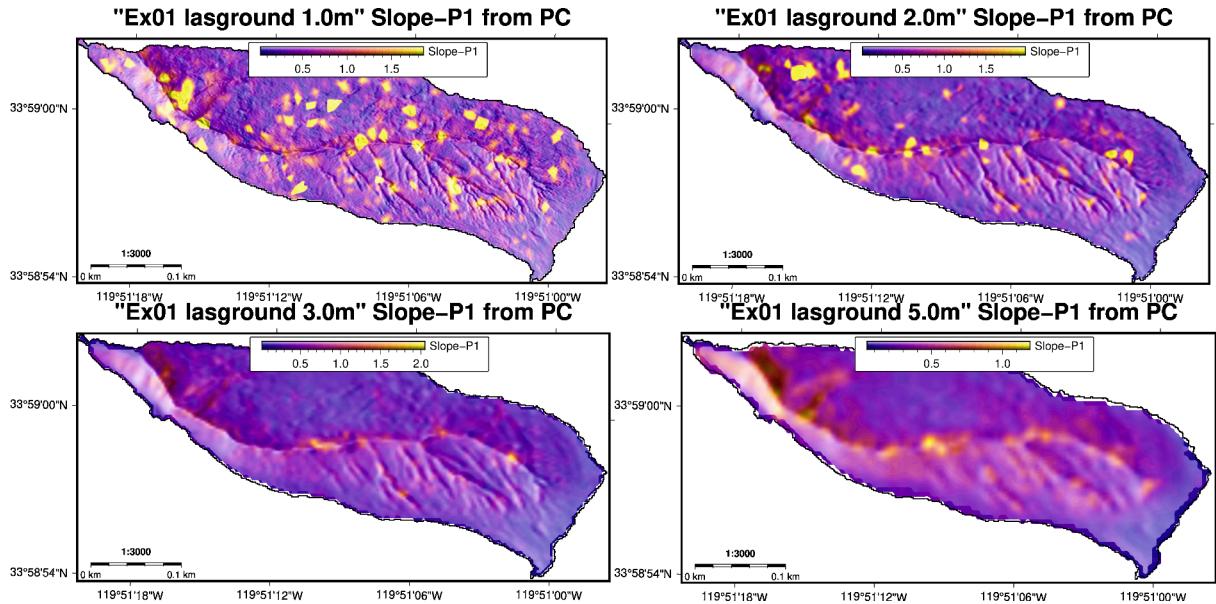


Figure 28: Deriving slopes for large neighborhood of points results in more realistic slope values. Here, the slopes for diameters of 1, 2, 3, and 5 m are shown. We only show the planar (polynomial order=1) slopes.

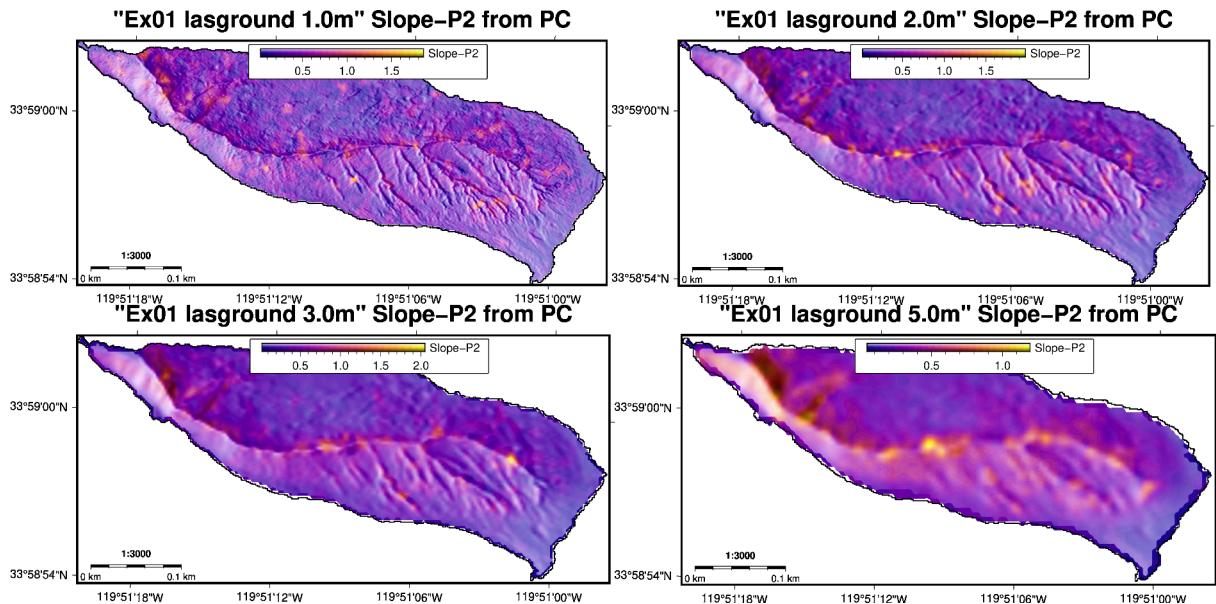


Figure 29: Deriving slopes for large neighborhood of points results in more realistic slope values. Here, the slopes for diameters of 1, 2, 3, and 5 m are shown. We only show the second order polynomials (polynomial order=2) slopes. These have generally a lower RMSE than polynomial orders=1.

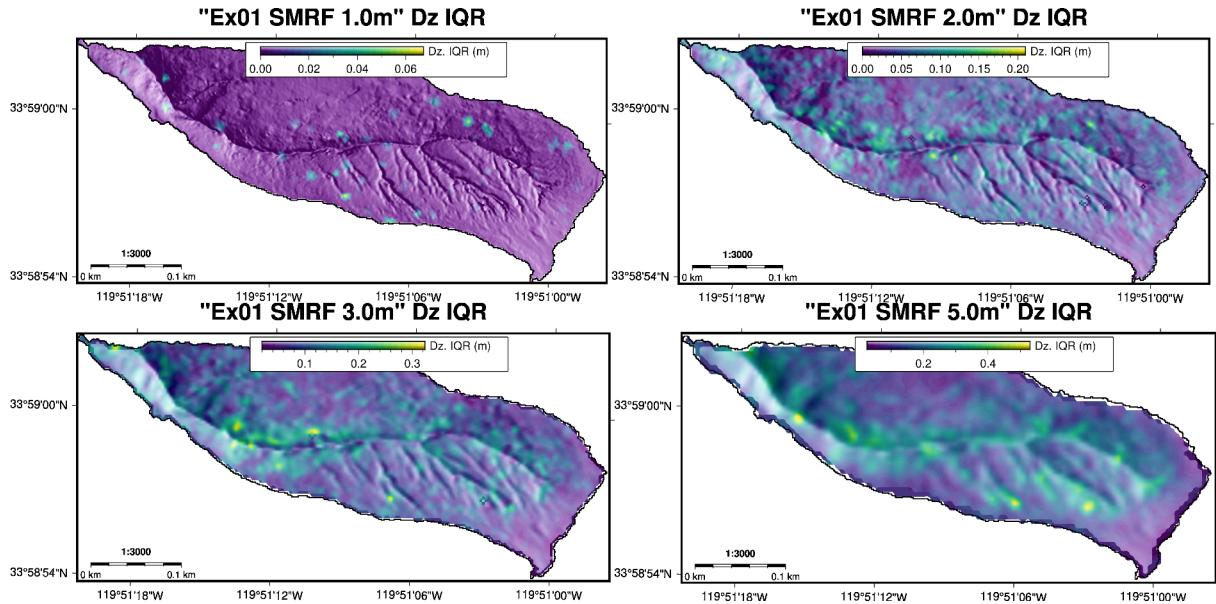


Figure 30: The IQR reflects channels and arroyos with increasing interpolation radii. Here, the slope-normalized elevation (IQR) for 1, 2, 3, and 5 m of interpolation diameters are shown.

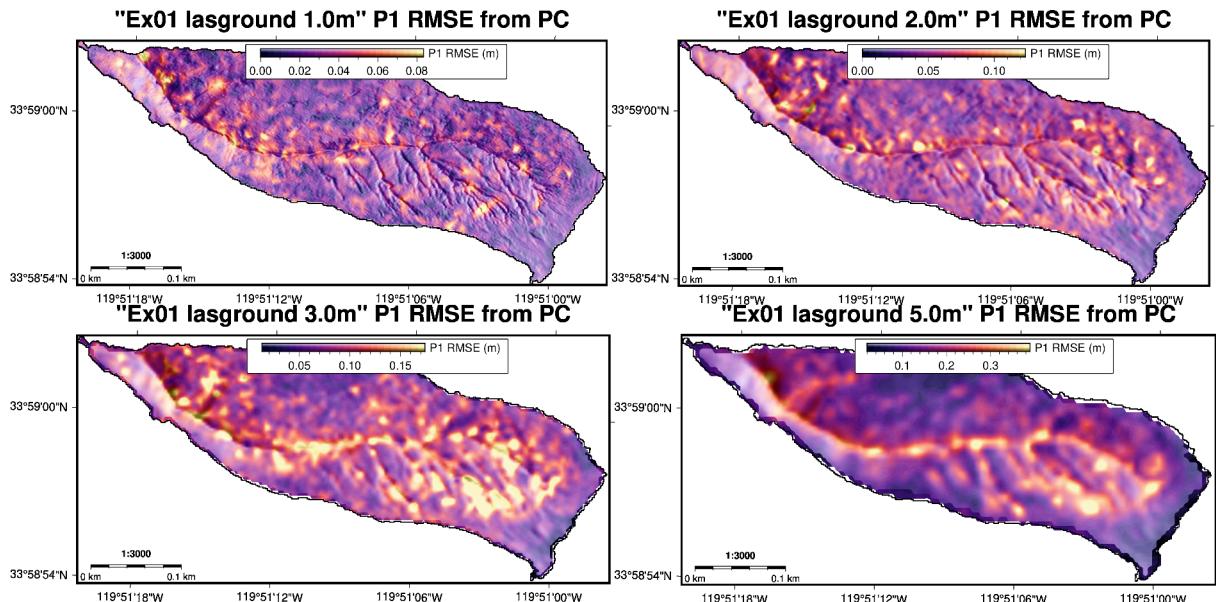


Figure 31: RMSE (m) from linear fits (polynomial order = 1) for radii 1, 2, 3, and 5 m are shown.

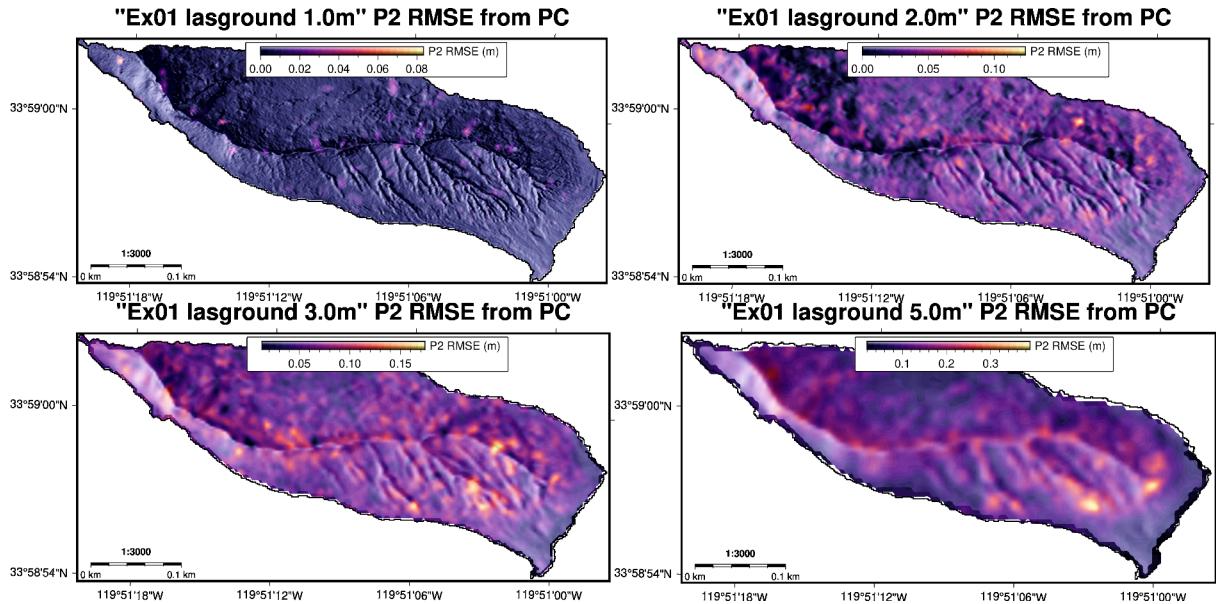


Figure 32: RMSE (m) from second-order fits (polynomial order = 2) for radii 1, 2, 3, and 5 m are shown.

6.2 Example 02 and PC densities

For a different catchment (stored in the folder Example 02), we have investigated the impact of PC densities on the outcome. We don't provide detailed processing steps, but only a short discussion of PC Densities.

In the *map* subdirectory several outputs are generated. First, we briefly investigate the impact on the DEM subsampling. We compare:

1. Original Pointcloud with n=574,092 points (DEM and PC density for 1m seed spacing: Figure 33)
Here, the following command has been used:

```
python -W ignore \
~/github/PC_geomorph_roughness/\
pc_geomorph_roughness.py
--inlas Blanca_in_Pozo_USGS_UTM11_NAD83_all_color_c12_SC12.laz
--raster_m_range "1 5 1"
--shapefile_clip ~/github/PC_geomorph_roughness/example_01/SC12.shp
--epsg_code 26911 --nr_of_cores 0 --create_geotiff 1 --create_gmt 1
--create_shapefiles 0 --create_las 1
--create_gmt_maps ~/github/PC_geomorph_roughness/\
example_01/example01_create_map_view_of_PC_geomorph_output_gmt.sh
--gmt_title "Blanca in Pozo (org PC)"
--gmt_basename "Pozo_Blanca_c12"
```

```
2>&1 | tee Blanca_in_Pozo_USGS_UTM11_NAD83_all_color_\
cl2_SC12_pc_geomorph_roughness_1_5_1.log
```

2. Subsampled PC with k=8 neighborhood points n=283,663 (DEM and PC density for 1m seed spacing: Figure 34)

```
python -W ignore \
~/Dropbox/soft/github/PC_geomorph_roughness/\
pc_geomorph_roughness.py
--inlas Blanca_in_Pozo_USGS_UTM11_NAD83_all_color_cl2_SC12.laz
--raster_m_range "1 5 1"
--shapefile_clip ~/github/PC_geomorph_roughness/example_01/SC12.shp
--epsg_code 26911 --nr_of_cores 0 --create_geotiff 1 --create_gmt 1
--create_shapefiles 0 --create_las 1
--subsample_1m_pc_k 8
--create_gmt_maps ~/github/PC_geomorph_roughness/example_01/\
example01_create_map_view_of_PC_geomorph_output_gmt.sh
--gmt_title "Blanca in Pozo (k=8)"
--gmt_basename "Pozo_Blanca_cl2_k8"
2>&1 | tee Blanca_in_Pozo_USGS_UTM11_NAD83_all_color_\
cl2_SC12_pc_geomorph_roughness_subsample_k8_1_5_1.log
```

3. Subsampled PC with probabilities based on densities to a fraction of 0.5 with n=287,046 (DEM and PC density for 1m seed spacing: Figure 35)

```
python -W ignore \
~/Dropbox/soft/github/PC_geomorph_roughness/\
pc_geomorph_roughness.py \
--inlas Blanca_in_Pozo_USGS_UTM11_NAD83_all_color_cl2_SC12.laz \
--raster_m_range "1 5 1" \
--shapefile_clip ~/github/PC_geomorph_roughness/example_01/SC12.shp \
--epsg_code 26911 --nr_of_cores 0 --create_geotiff 1 --create_gmt 1 \
--create_shapefiles 0 --create_las 1 \
--subsample_1m_pc_p 0.8 \
--create_gmt_maps \
~/github/PC_geomorph_roughness/example_01/\
example01_create_map_view_of_PC_geomorph_output_gmt.sh \
--gmt_title "Blanca in Pozo (p=0.8)" \
--gmt_basename "Pozo_Blanca_cl2_p08" \
2>&1 | tee Blanca_in_Pozo_USGS_UTM11_NAD83_all_color_\
cl2_SC12_pc_geomorph_roughness_subsample_p08_1_5_1.log
```

4. Subsampled PC with probabilities based on densities to a fraction of 0.8 with n=459,273 (DEM

and PC density for 1m seed spacing: Figure 36)

```
python -W ignore \
~/Dropbox/soft/github/PC_geomorph_roughness/\
pc_geomorph_roughness.py \
--inlas Blanca_in_Pozo_USGS_UTM11_NAD83_all_color_cl2_SC12.laz \
--raster_m_range "1 5 1" \
--shapefile_clip \
~/github/PC_geomorph_roughness/example_01/SC12.shp \
--epsg_code 26911 --nr_of_cores 0 --create_geotiff 1 \
--create_gmt 1 --create_shapefiles 0 \
--create_las 1 --subsample_1m_pc_p 0.8 \
--create_gmt_maps \
~/github/PC_geomorph_roughness/example_01/\
example01_create_map_view_of_PC_geomorph_output_gmt.sh \
--gmt_title "Blanca in Pozo (p=0.8)" \
--gmt_basename "Pozo_Blanca_cl2_p08" \
2>&1 | tee Blanca_in_Pozo_USGS_UTM11_NAD83_all_color_\
cl2_SC12_pc_geomorph_roughness_subsample_p08_1_5_1.log
```

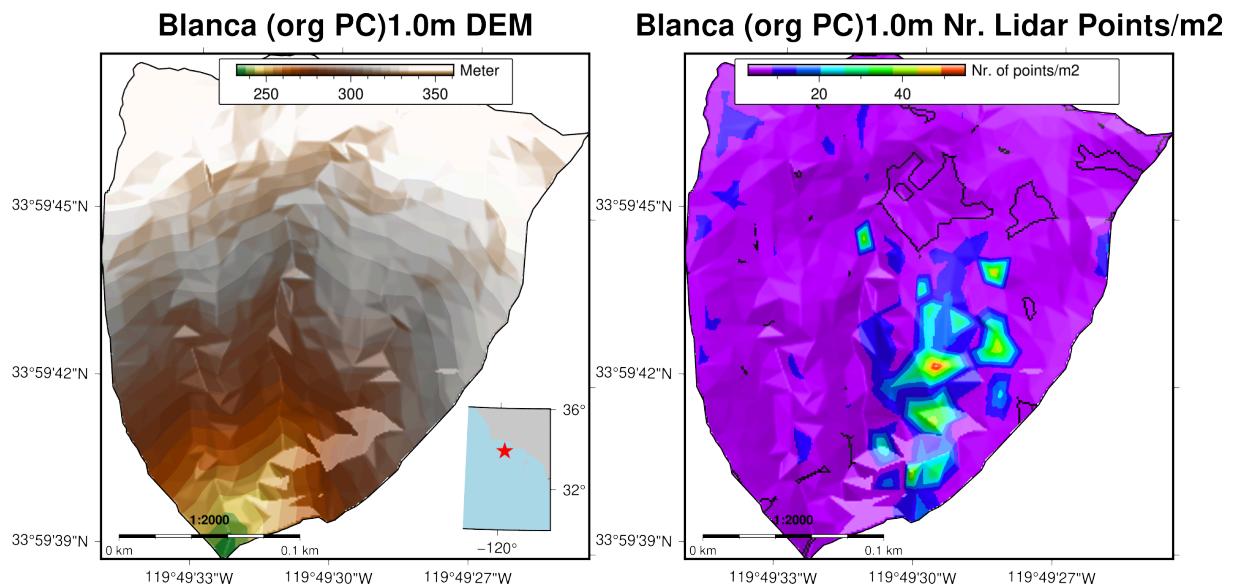


Figure 33: DEM and PC density for 1m seed spacing: original point cloud, no subsampling. Note the large range of point densities (n=574,092).

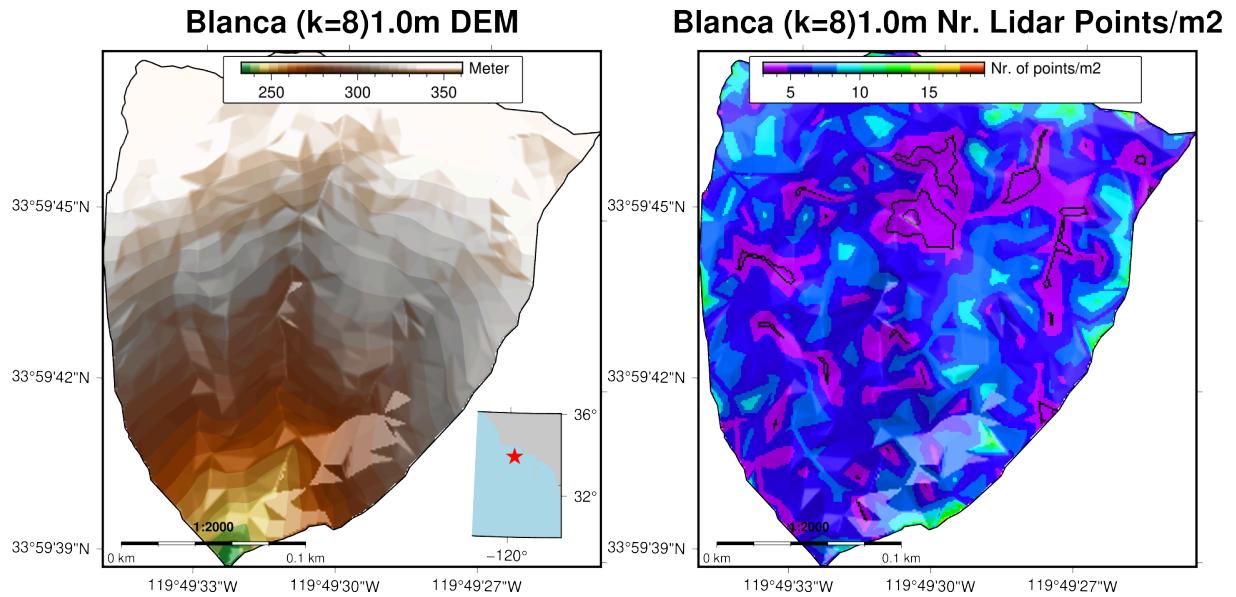


Figure 34: DEM and PC density for 1m seed spacing: subsampled point cloud with $k=8$ neighborhood points ($n=283,663$). Note the greatly reduced variability in point densities.

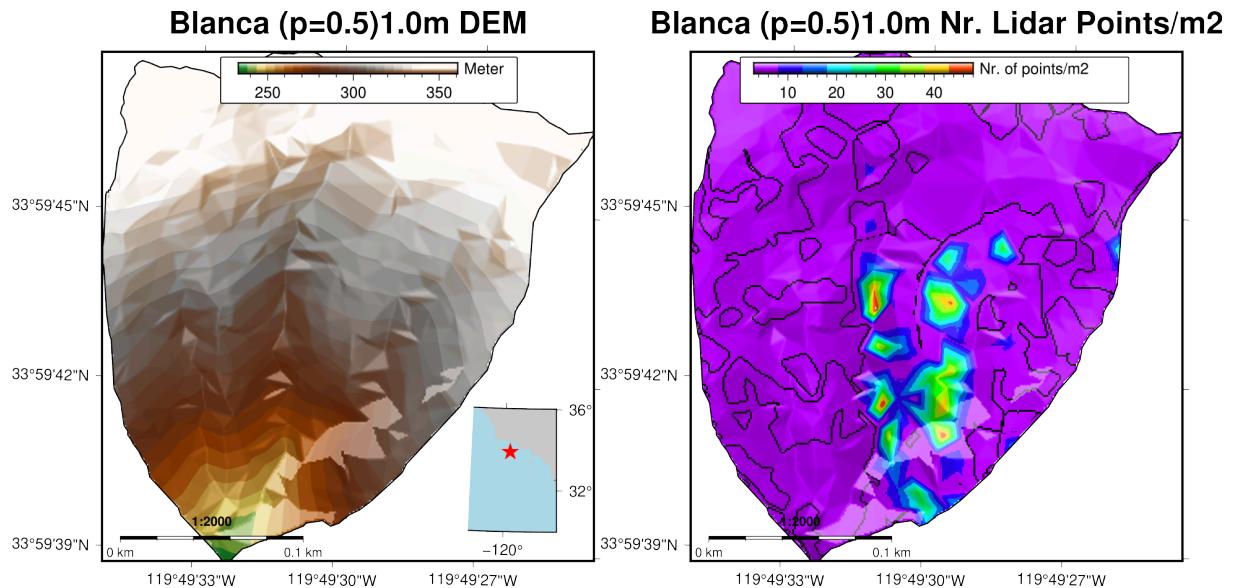


Figure 35: DEM and PC density for 1m seed spacing: subsampled point cloud with probabilities to create a PC with 50% of the original points ($n=287,046$). Point densities are very similar and point cloud has been homogenized.

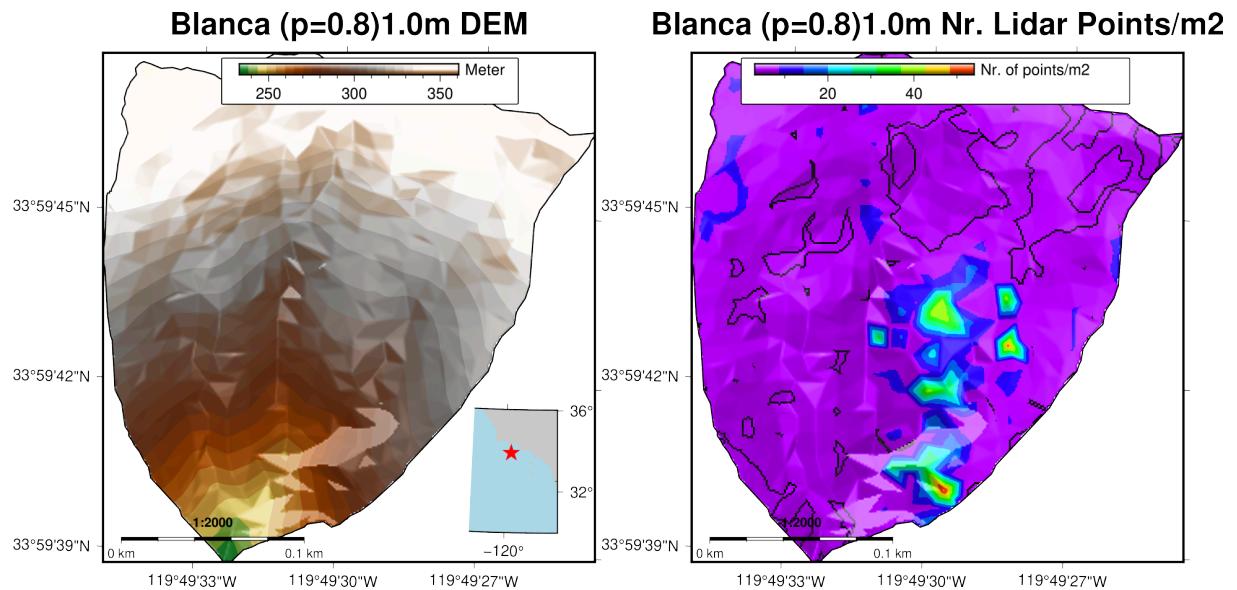


Figure 36: DEM and PC density for 1m seed spacing: subsampled point cloud with probabilities to create a PC with 80% of the original points ($n=459,273$). Point densities are still moderately high, but reduced compared to original point cloud.

A comparison of point densities across several neighborhood sizes reveals that the discrepancies tend to homogenize (Figure 37).

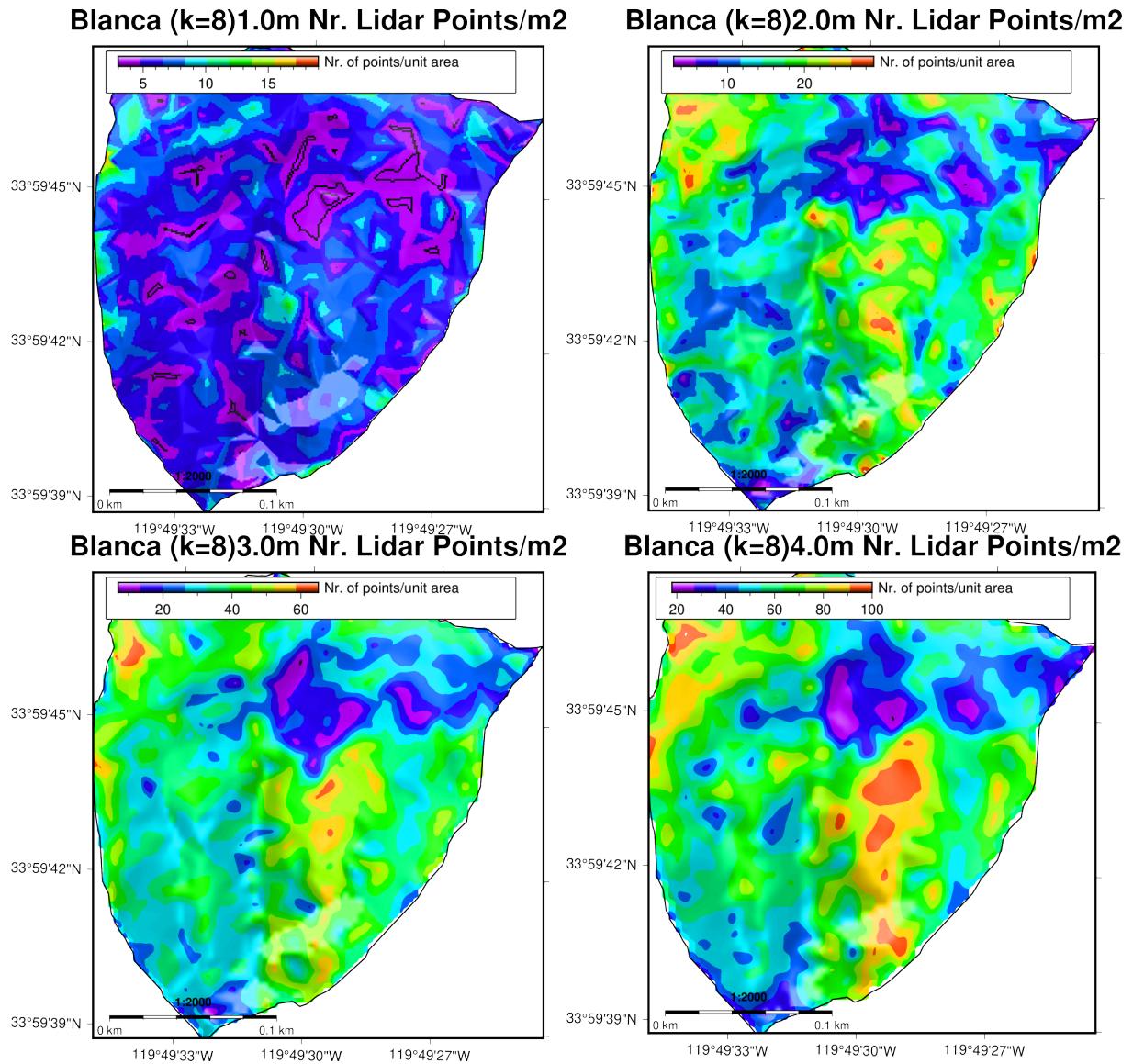


Figure 37: PC density for 1, 2, 3, and 4m seed spacing for $k=8$ points/ m^2 subsampling. Note that discrepancies tend to homogenize at larger grid-cell sizes. There were $n=459,273$ original points.

6.3 Example 03

In the example, we just list the steps and provide the setup to run the LAS file in folder example_03.

6.3.1 Pre-processing and PC classification

```
cd example_03
```

```
pdal translate Pozo_USGS_UTM11_NAD83_cat17.laz \
Pozo_USGS_UTM11_NAD83_cat17_SMRF_cl2.las --json example03_PDAL_SMRF_pipeline.json
```

Here, we experienced some issues with PDAL-SMRF (not all ground points were classified) and we relied on the lasground classification:

```
wine /opt/LAStools/bin/lasclassify.exe -i Pozo_USGS_UTM11_NAD83_cat17.laz -olaz \
-set_user_data 0 -set_classification 0 -o Pozo_USGS_UTM11_NAD83_cat17_uncl.laz
wine /opt/LAStools/bin/lasnoise.exe -i Pozo_USGS_UTM11_NAD83_cat17_uncl.laz -step_xy 2 \
-step_z 1 -isolated 5 -olaz -o Pozo_USGS_UTM11_NAD83_cat17_uncln.laz
wine /opt/LAStools/bin/lasground.exe -i Pozo_USGS_UTM11_NAD83_cat17_uncln.laz \
-by_flightline -wilderness -extra_fine -offset 0.25 -stddev 20 -step 1 -spike 0.5 \
-bulge 0.5 -olaz -o Pozo_USGS_UTM11_NAD83_cat17_clg.laz
wine /opt/LAStools/bin/las2las.exe -i Pozo_USGS_UTM11_NAD83_cat17_clg.laz -keep_class \
2 -olaz -o Pozo_USGS_UTM11_NAD83_cat17_clg_cl2.laz
mkdir dtm_interp
wine /opt/LAStools/bin/blast2dem.exe -keep_class 2 -utm 11N -nad83 -meter \
-elevation_meter -merged -step 1 -i Pozo_USGS_UTM11_NAD83_cat17_clg_cl2.laz -o \
dtm_interp/Pozo_USGS_UTM11_NAD83_cat17_clg_cl2_1m.tif
```

This original PC is provided in [example_03/Pozo_USGS_UTM11_NAD83_cat17.laz](#) and the lastools-classified PC [example_03/Pozo_USGS_UTM11_NAD83_cat17_clg.laz](#).

6.3.2 Density-based subsampling and GMT map generation

We use the provided GMT script (example03_create_map_view_of_PC_geomorph_output_gmt.sh) to generate map views from the subsampled PC.

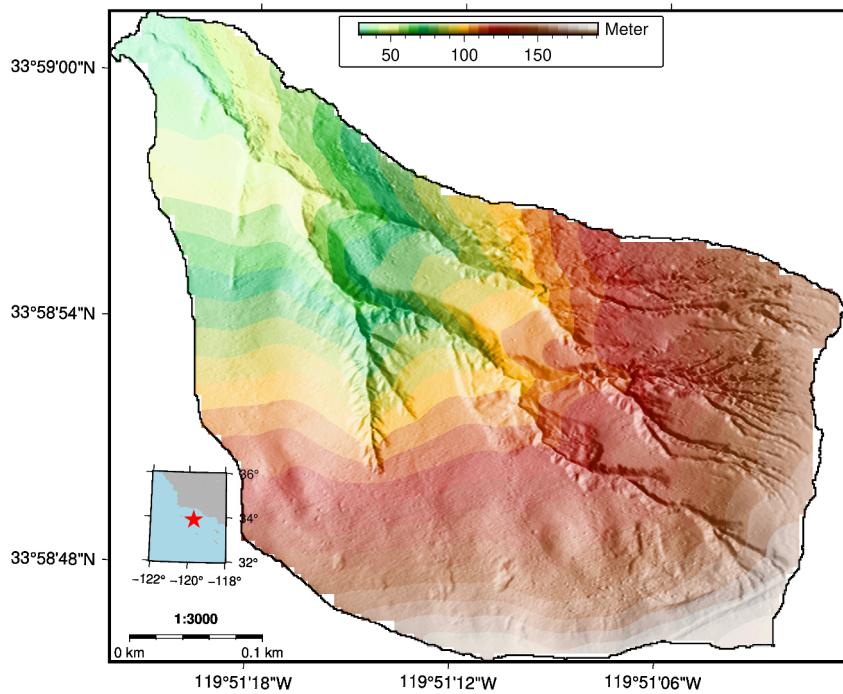
NOTE: Make sure to give the full path to the Shapefile used as clip and for the GMT Shell script!

```
python -W ignore ~/github/PC_geomorph_roughness/\
PC_geomorph_roughness/pc_geomorph_roughness.py \
-i Pozo_USGS_UTM11_NAD83_cat17_clg_cl2.laz \
--raster_m_range "1 10 1" \
--shapefile_clip ~/github/PC_geomorph_roughness/\
example_03/Pozo_DTM_noveg_UTM11_NAD83_cat17.shp \
--epsg_code 26911 --nr_of_cores 0 --create_geotiff 1 --create_gmt 0 \
--create_shapefiles 0 --create_las 1 \
--dem_fname ~/github/PC_geomorph_roughness/\
example_03/dtm_interp/Pozo_USGS_UTM11_NAD83_cat17_clg_cl2_1m.tif \
--subsample_1m_pc_p 0.8 \
--create_gmt_maps ~/github/PC_geomorph_roughness/\  
67
```

```
example_03/example03_create_map_view_of_PC_geomorph_output_gmt.sh \  
--gmt_title "Ex03 lasground in Pozo" \  
--gmt_basename "Ex03_cl2" \  
2>&1 | tee \  
Pozo_USGS_UTM11_NAD83_cat17_lasground_cl2_pc_geomorph_roughness_subsample_p08_1_10_1.log
```

This will generate a set of output maps with GMT that are illustrated below (Figures ??, ??, ??, 41, 42, 43).

"Ex03 lasground in Pozo 1.0m" interpolated DEM



"Ex03 lasground in Pozo 1.0m" Delta DEM

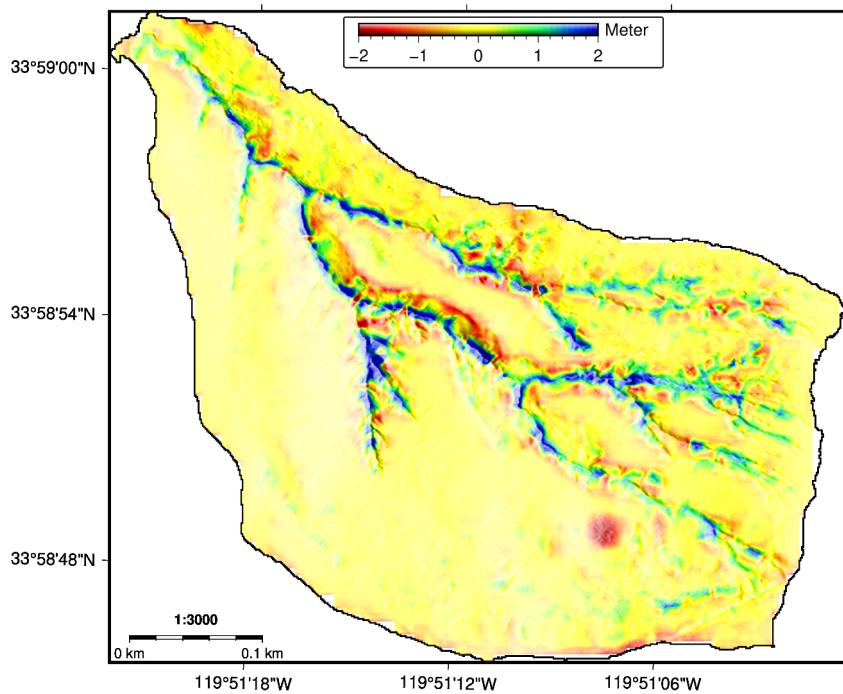
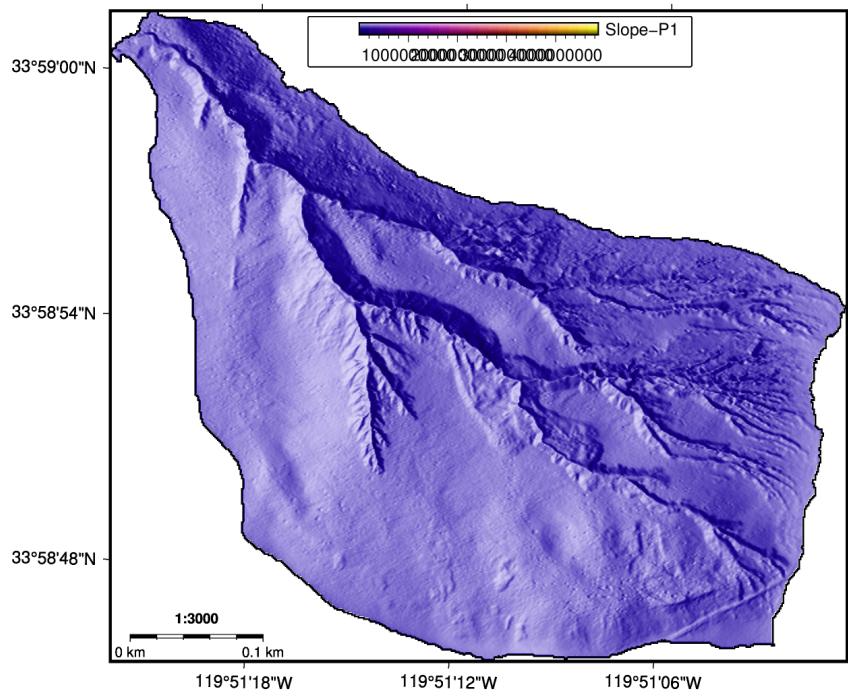


Figure 38: Output of 1m DEM generated from the interpolated point cloud and difference DEM between the mean seed height and the interpolated DEM for Example03. Note that the interpolated DEM is based on all ground points, while the mean-seed point DEM used the largely reduced seed point PC.

"Ex03 lasground in Pozo 1.0m" Slope-P1 from PC



"Ex03 lasground in Pozo 1.0m" Slope-P2 from PC

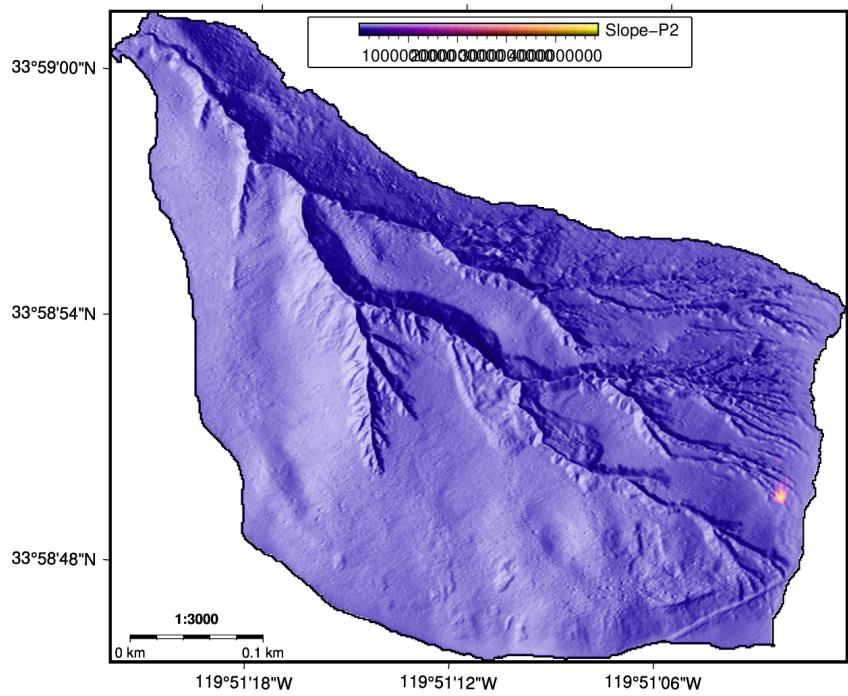
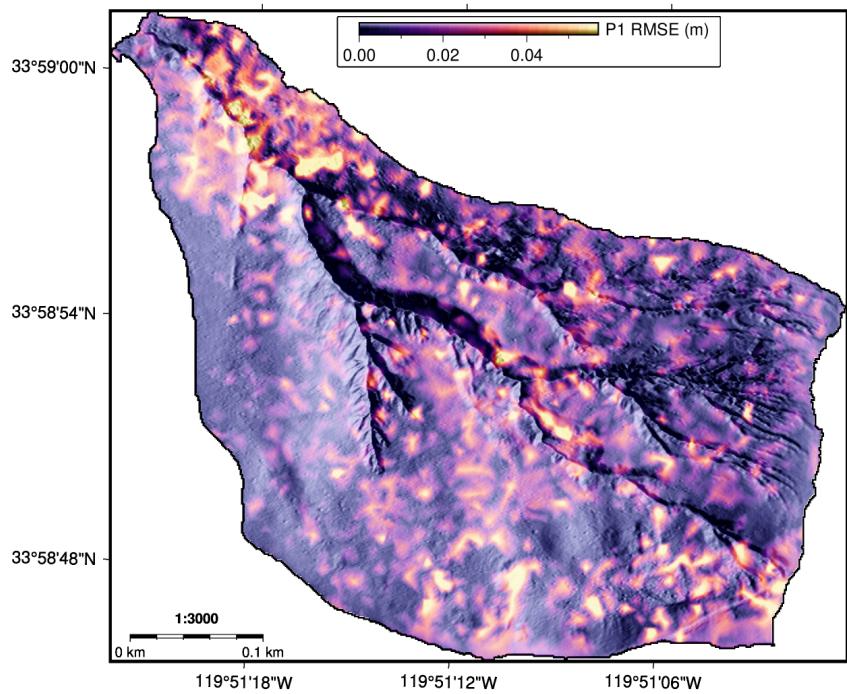


Figure 39: Slope measurements for Example 03.

"Ex03 lasground in Pozo 1.0m" P1 RMSE from PC



"Ex03 lasground in Pozo 1.0m" P2 RMSE from PC

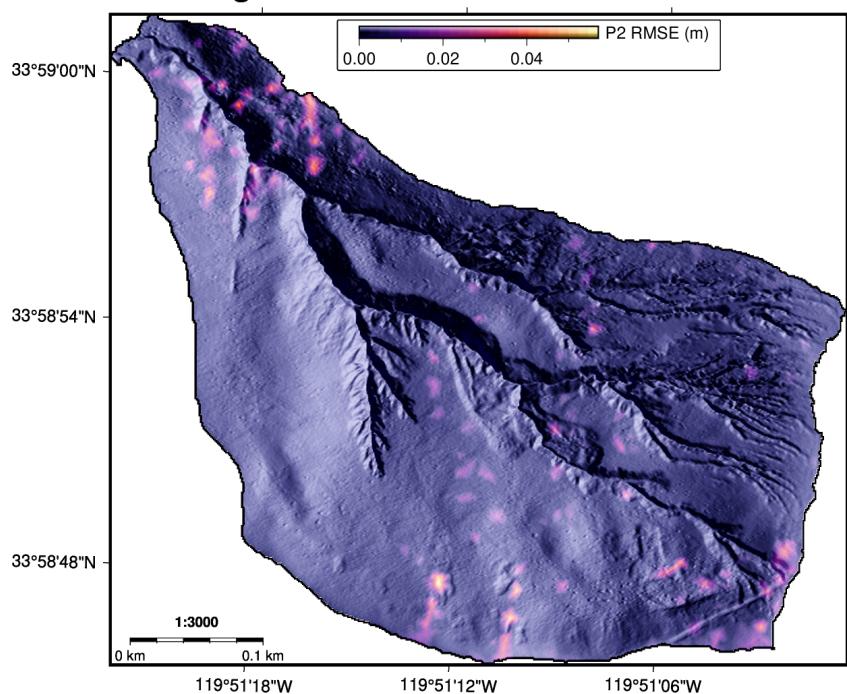


Figure 40: RMSE measurements for Example 03.

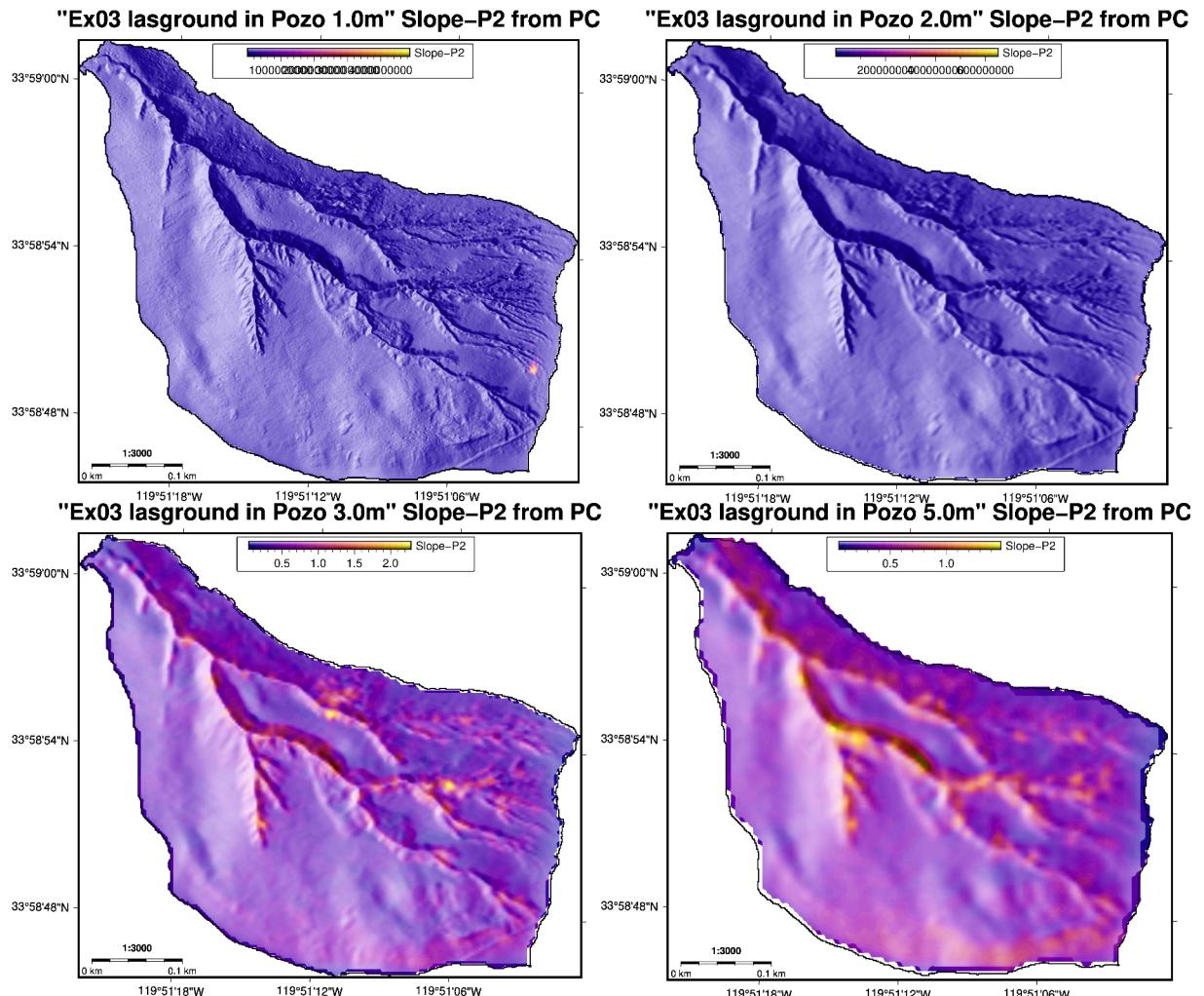


Figure 41: Slope comparison for Example 03 from 1 to 5m diameter.

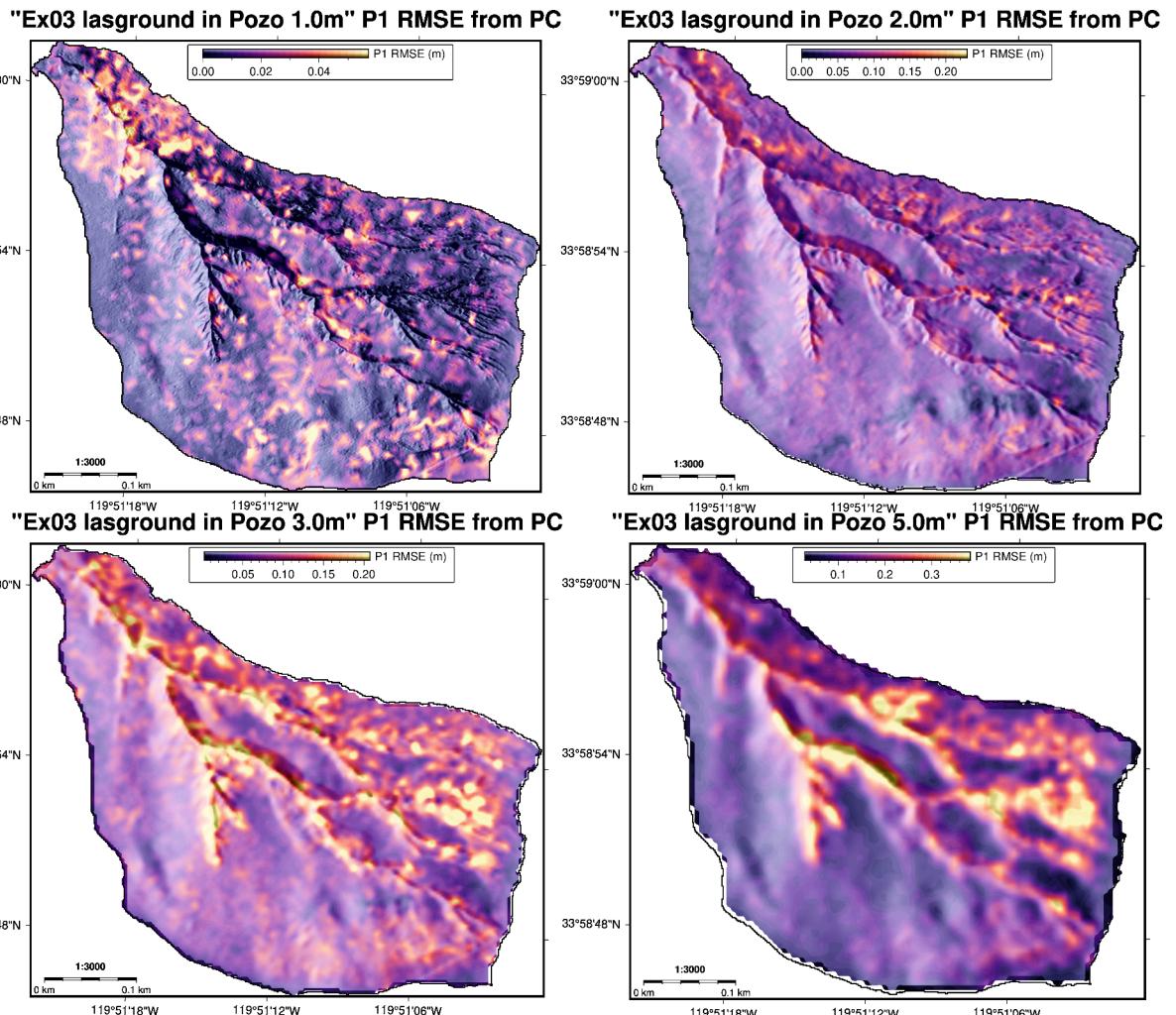


Figure 42: RMSE comparison for Example 03 from 1 to 5m diameter.

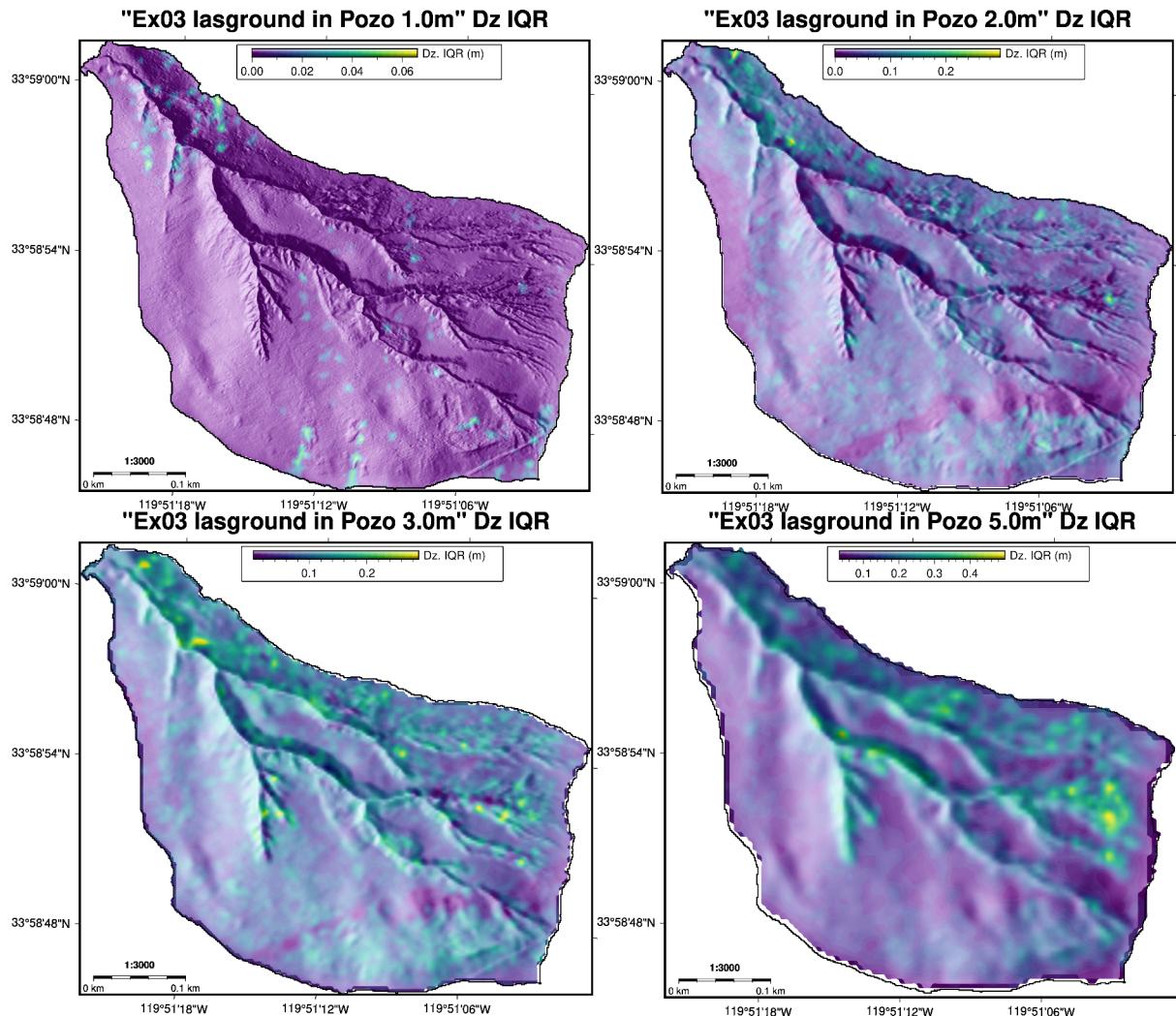


Figure 43: IQR of slope-normalized surface for diameter of 1, 2, 3, and 5m.

6.4 Example 04

In this last example, we use a larger area covering the Blanca formation of the Pozo catchment (cf.). This area contains almost 3 Million points.

6.4.1 Pre-processing and PC classification

We rely on ground classification with LASTools:

```
cd example_04
```

```

wine /opt/LAStools/bin/lasclassify.exe -i Pozo_WestCanada.laz -olaz -set_user_data 0 \
-set_classification 0 -o Pozo_WestCanada_uncl.laz
wine /opt/LAStools/bin/lasnoise.exe -i Pozo_WestCanada_uncl.laz -step_xy 2 -step_z 1 \
-isolated 5 -olaz -o Pozo_WestCanada_uncln.laz
wine /opt/LAStools/bin/lasground.exe -i Pozo_WestCanada_uncln.laz -by_flightline \
-wilderness -extra_fine -offset 0.25 -stddev 20 -step 1 -spike 0.5 -bulge 0.5 \
-olaz -o Pozo_WestCanada_clg.laz
wine /opt/LAStools/bin/las2las.exe -i Pozo_WestCanada_clg.laz -keep_class 2 -olaz -o \
Pozo_WestCanada_clg_cl2.laz
mkdir dtm_interp
wine /opt/LAStools/bin/blast2dem.exe -keep_class 2 -utm 11N -nad83 -meter \
-elevation_meter -merged -step 1 -i Pozo_WestCanada_clg_cl2.laz -o \
dtm_interp/Pozo_WestCanada_clg_cl2_1m.tif

```

This original PC is provided in [example_04/Pozo_WestCanada.laz](#) and the lastools-classified PC [example_04/Pozo_WestCanada_clg.laz](#).

6.4.2 Density-based subsampling and GMT map generation

We use the provided GMT script (example04_create_map_view_of_PC_geomorph_output_gmt.sh) to generate map views from the subsampled PC.

NOTE: Make sure to give the full path to the Shapefile used as clip and for the GMT Shell script!

```

python -W ignore ~/github/PC_geomorph_roughness/\
PC_geomorph_roughness/pc_geomorph_roughness.py \
-i Pozo_WestCanada_clg_cl2.laz \
--raster_m_range "1 5 1" \
--shapefile_clip ~/github/PC_geomorph_roughness/\
example_04/WestCanada.shp \
--epsg_code 26911 --nr_of_cores 0 --create_geotiff 1 --create_gmt 0 \
--create_shapefiles 0 --create_las 1 \
--dem_fname ~/github/PC_geomorph_roughness/\
example_04/dtm_interp/Pozo_WestCanada_clg_cl2_1m.tif \
--subsample_1m_pc_p 0.8 \
--create_gmt_maps ~/github/PC_geomorph_roughness/\
example_04/example04_create_map_view_of_PC_geomorph_output_gmt.sh \
--gmt_title "Ex04 lasground in Pozo" \
--gmt_basename "Ex04_cl2" \
2>&1 | tee \
Pozo_USGS_UTM11_NAD83_Pozo_WestCanada_clg_cl2_pc_geomorph_roughness_subsample_p08_1_5_1.log

```

This will generate a set of output maps with GMT that are illustrated below (Figures ??, ??, ??, ??), and ??.

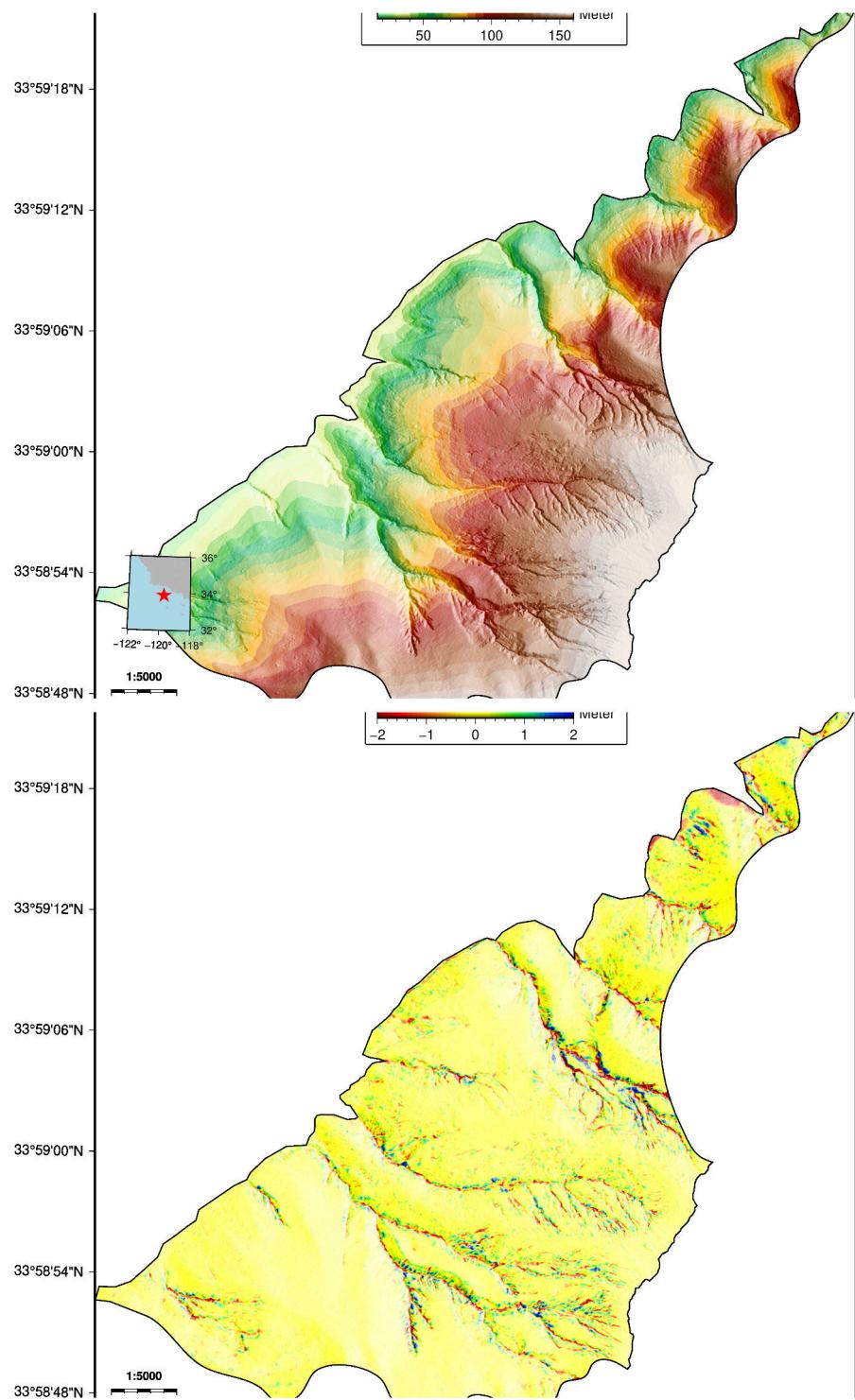


Figure 44: DEM view of Example 04. Output of 1m DEM generated from the interpolated point cloud and difference DEM between the mean seed height and the interpolated DEM. Note that the interpolated DEM is based on all ground points, while the mean-seed point DEM used the largely reduced seed-point PC.

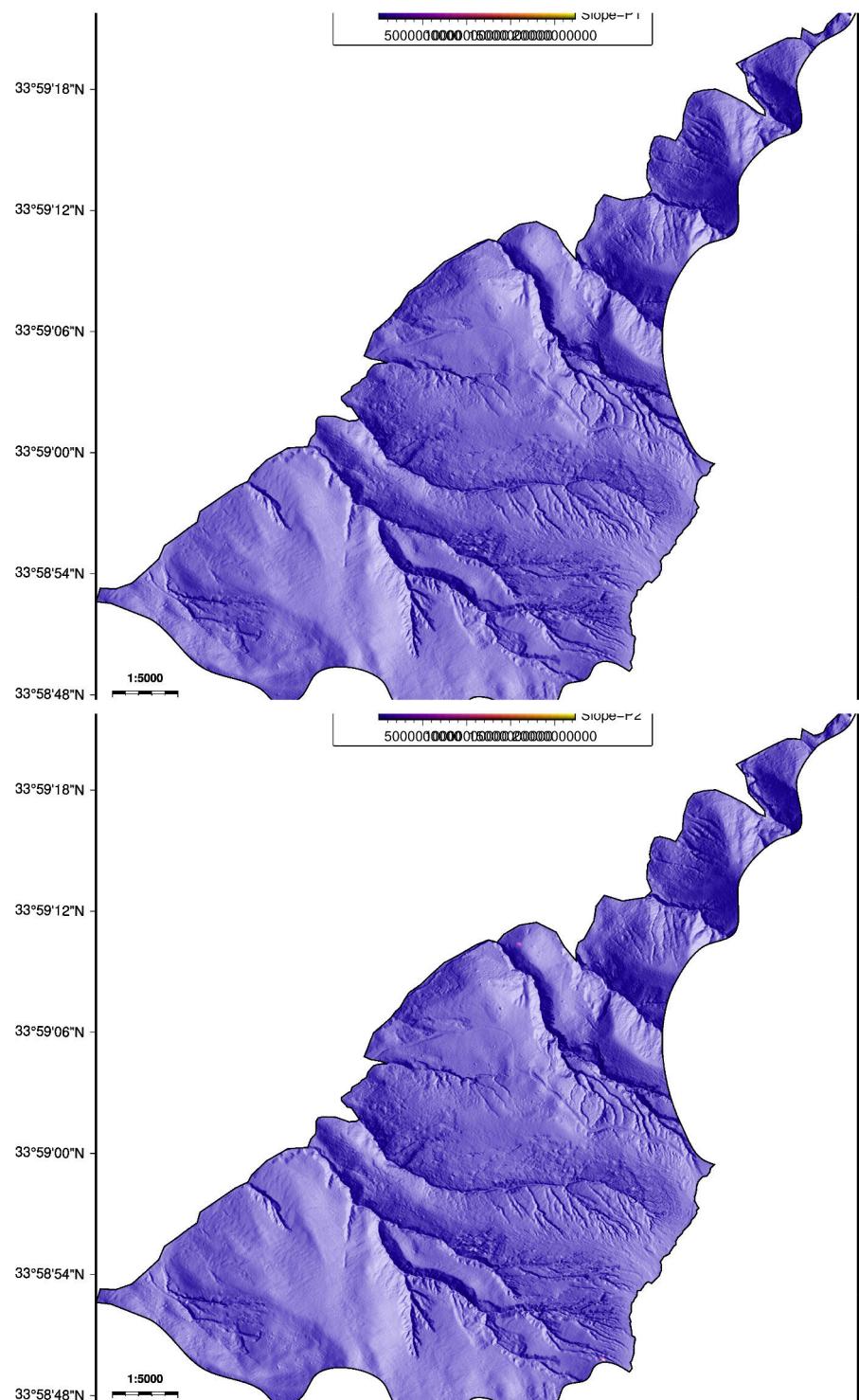


Figure 45: Slope measurements for Example 04 at 1m diameter ($r=0.5$).

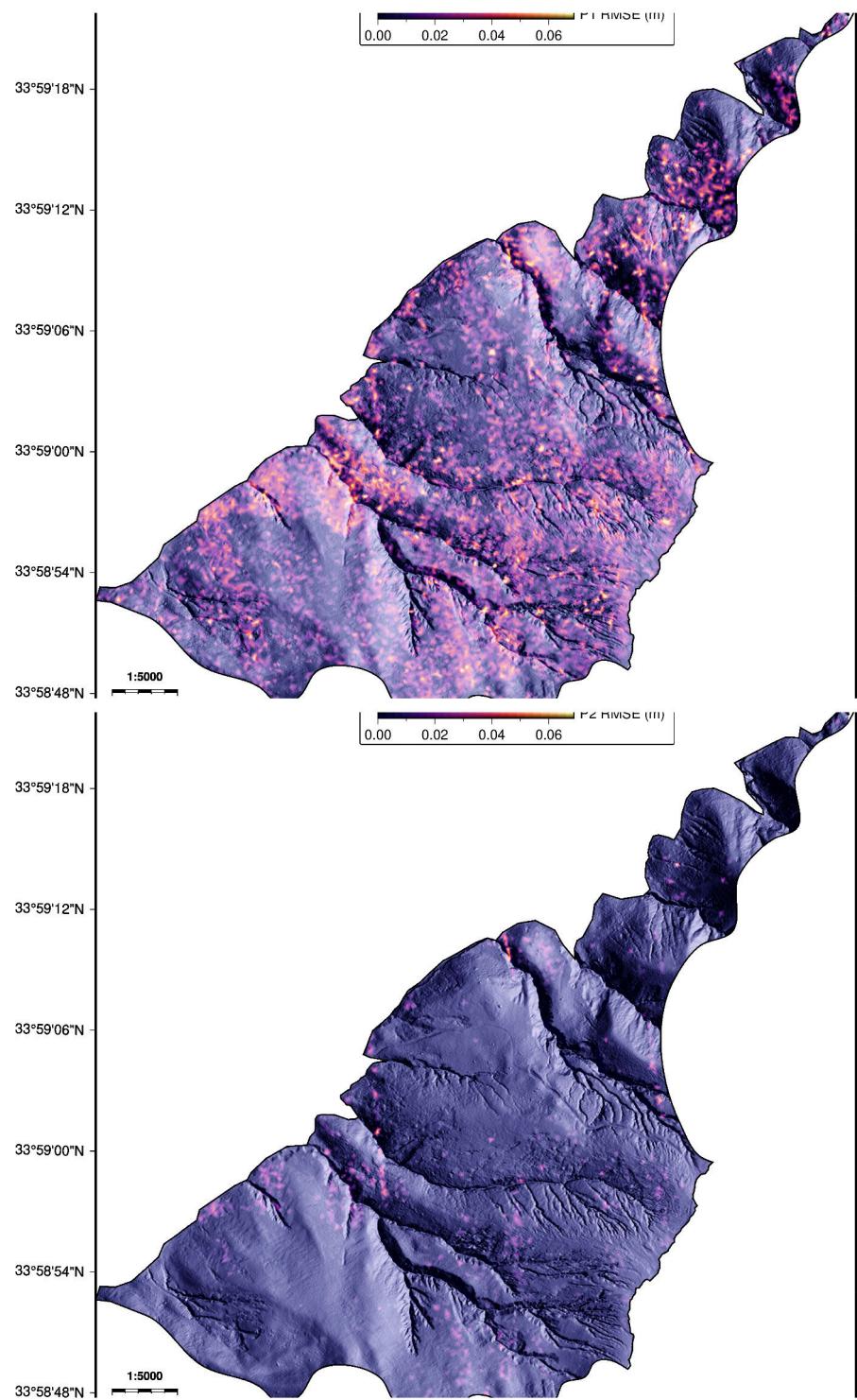


Figure 46: RMSE measurements for Example 04 at 1m diameter ($r=0.5$).

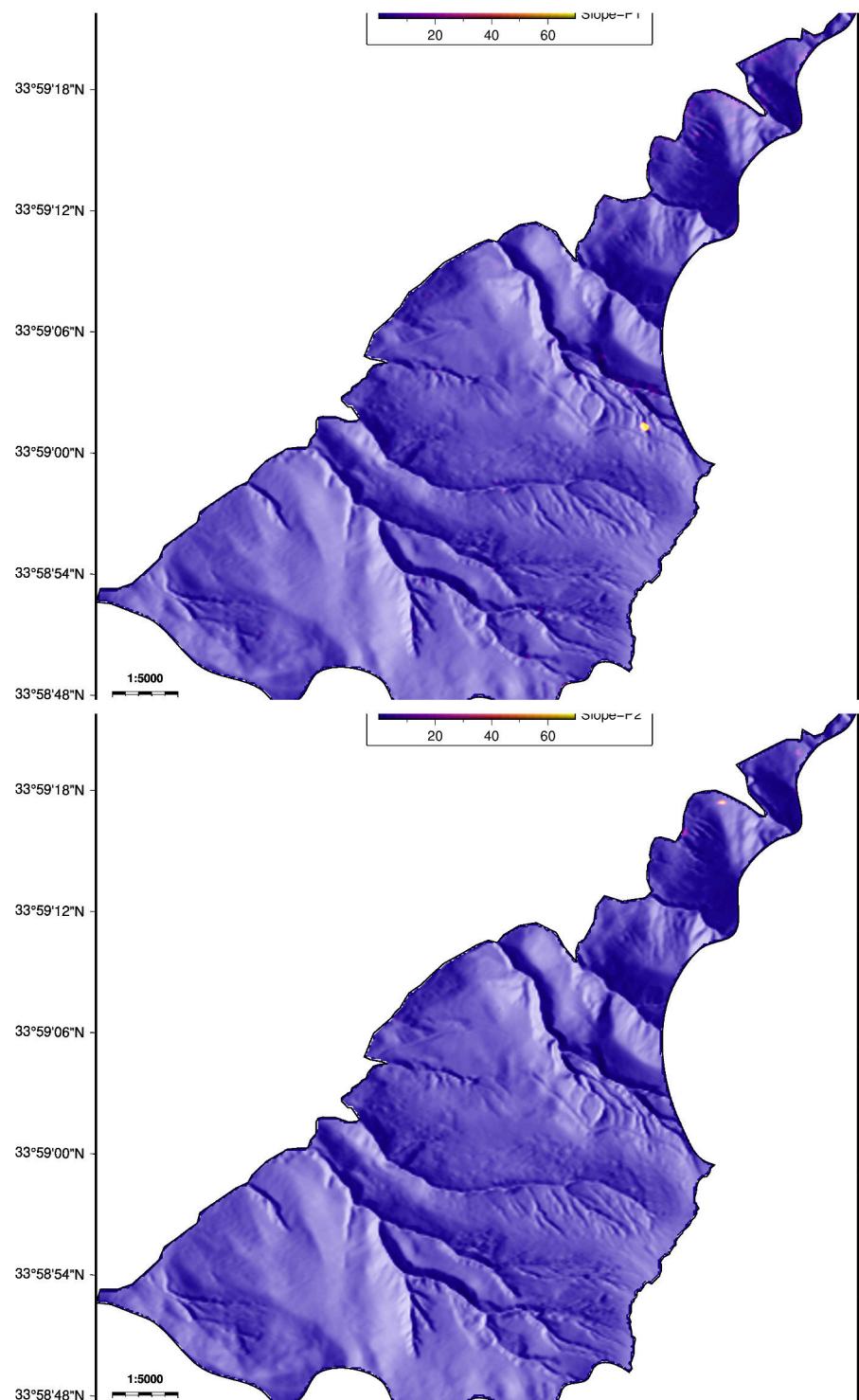


Figure 47: Slope measurements for Example 04 at 3m diameter ($r=1.5$).

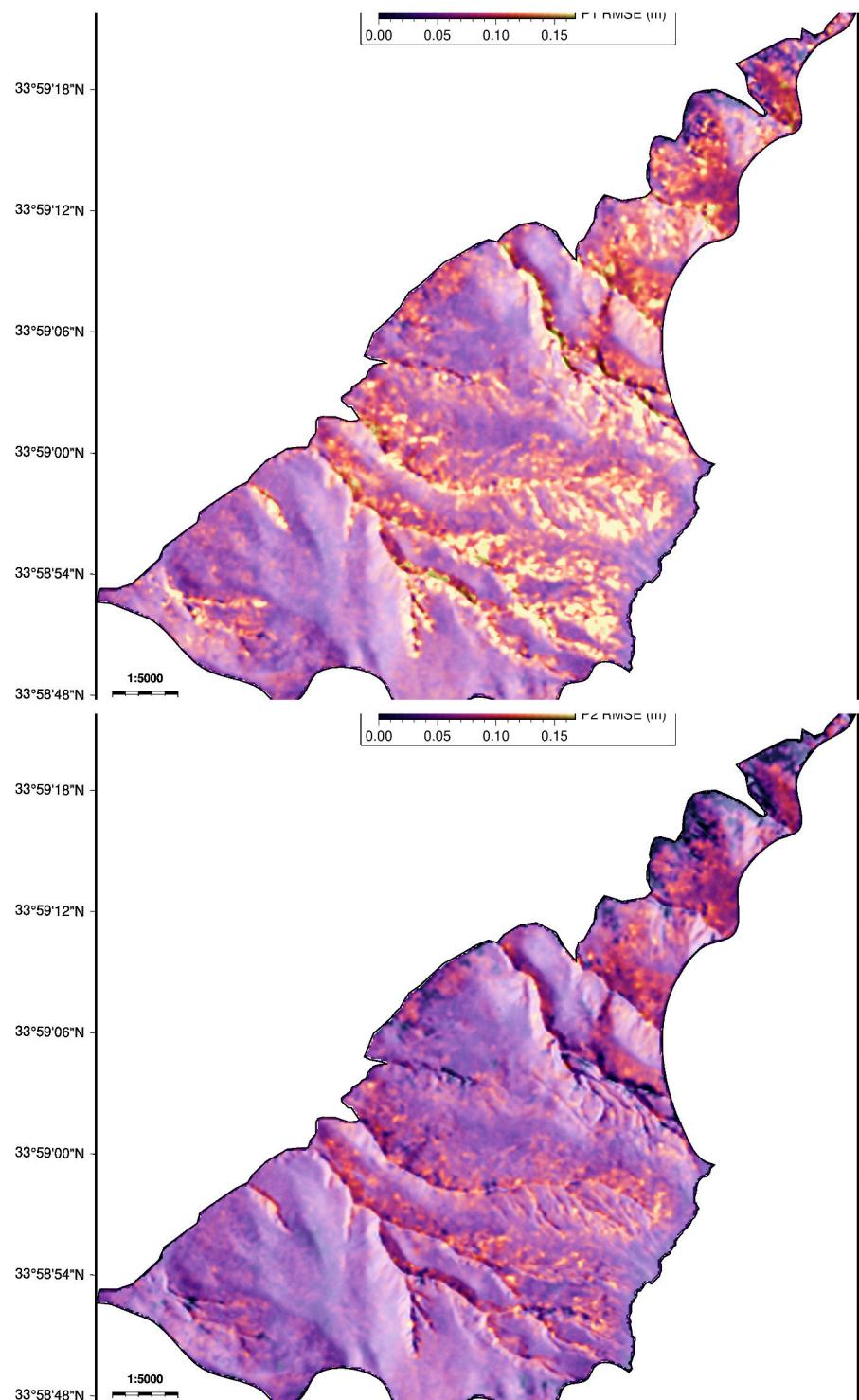


Figure 48: RMSE measurements for Example 04 at 3m diameter ($r=1.5$).