Jupyter notebook used in the paper:

Aeolian dune modelling from airborne LiDAR, terrestrial LiDAR and Structure from Motion--Multi View Stereo

by Carlos H. Grohmann et al - 2019/2020
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Please check the GitHub repo for the final reference to the paper (here (https://github.com/CarlosGrohmann/scripts_papers/tree/master/garopaba_als_sfm_tls))

Shapefiles provided with this script:

- mask_sfm - mask for ALS and SfM interpolation and comparison
- mask_volume - mask for volume calculation (ALS and SfM)
- area_als_dunes - mask for the entire dunefield (ALS coverage)
- mask_tls - mask of TLS survey area
- mask_tls_sfm - mask used to constrain random points (TLS x SfM)
- crests_als_2010 - crestlines of 2010 (ALS)
- crests_sfm_2019 - crestlines of 2019 (SfM)
- displacement_crests_2010_2019 - lines connecting 2010 and 2019 crests
- dgps_garopaba - dgps GCPs

Point cloud data used in this paper is available via OpenTopography

- Airborne LiDAR (2010) - http://dx.doi.org/10.5069/G9DN430Z (http://dx.doi.org/10.5069/G9DN430Z)
- SfM-MVS (2019) - http://dx.doi.org/10.5069/G9DV1H19 (http://dx.doi.org/10.5069/G9DV1H19)
- Terrestrial LiDAR (2019) - https://doi.org/10.5069/G9CN7228 (https://doi.org/10.5069/G9CN7228)

Notes:
This is the full research script, meaning some of the stuff here was not used in the final paper, like r3.volume and the normality tests of displacement length

This notebook uses f-strings - needs python 3.6+

Since we use python 3, we need GRASS-GIS 7.8+

The external file 'azim_p3.py' has the function to calculate azimuth and length of lines

My GRASS wasn't working witb LibLAS for direct LAS import, so I converted it to TXT. Depending on the GRASS installation, you can use v.in.lidar or v.in.pdal as well

Quick links to notebook sections

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Imports and auxiliar functions.

In [1]:
```
# import python libraries
import sys, os, itertools
import numpy as np
import scipy.stats as ss
import matplotlib.pyplot as plt
import matplotlib as mpl
import pandas as pd
import seaborn as sns
import rasterio as rio
# import rasterio.mask as riom
import xarray as xr
# import fiona as fna
# import geopandas as gpd
import subprocess
from IPython.display import Image # can use this to display GRASS m
aps
# stats
from statsmodels.graphics.gofplots import qqplot
from scipy.stats import linregress
```

In [2]:
```
# import module to calculate azimuth of lines -- requires python GD
AL/OGR libraries
# mac fix (gdal+pyenv): # https://gist.github.com/cspanring/5680334
#gistcomment-2898629

# on Linux, I needed to set this or jupyter wouldn't find the ogr m
odule:
if sys.platform == "linux" or sys.platform == "linux2":
    sys.path.append('/usr/lib/python3/dist-packages')
import azim_p3
```

In [3]:
```
# helper func: round to nearest 5
def round5(x):
    rounded = int(round(x/5.0)*5.0)
    return rounded
```

In [4]:
```
# error measurements
def err_mse(x1, x2, axis=0):
    """mean squared error"""
    x1 = np.asanyarray(x1)
    x2 = np.asanyarray(x2)
    return np.mean((x1-x2)**2, axis=axis)

def err_rmse(x1, x2, axis=0):
    """root mean squared error"""
    x1 = np.asanyarray(x1)
    x2 = np.asanyarray(x2)
    return np.sqrt(err_mse(x1, x2, axis=axis))

def err_mae(x1, x2, axis=0):
    """mean absolute error"""
    x1 = np.asanyarray(x1)
    x2 = np.asanyarray(x2)
    return np.mean(np.abs(x1-x2), axis=axis)
```

In [5]:
```
def fdr(df):
    ''' Freedman–Diaconis rule to calculate optimal bin size of his
tograms
    '''
    q25 = df.quantile(0.25)
    q75 = df.quantile(0.75)
    len_max = df.max()
    len_min = df.min()
    len_n = len(df)
    IQR = q75 - q25
    bin_width = 2. * IQR * (len_n)**(-1./3.)
    nbins = (len_max - len_min)/bin_width
    return int(nbins)
```

In [6]:
```
# aux func
def raster_as_array(raster):
    ''' return GRASS raster as numpy array - remove null values '''
    grass.run_command('g.region', raster=raster, flags='a')
    raster_array = garray.array()
    raster_array.read(raster, null=np.nan)
    raster_array_flat = raster_array.flatten(order='C')
    raster_1d = raster_array_flat[~np.isnan(raster_array_flat)]
    return raster_1d
```

In [7]:
```
# matplotlib figures appear inline in the notebook rather than in a
new window.
%matplotlib inline
```

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GRASS setup

This notebook was made for a Linux machine, since there are still some issues with GRASS 7.8+ on MacOS. I left an example in the cell below of how I was using it with two systems, using sys.platform

In [8]:
```
# If you use two systems this makes things a bit easier
# I had this for setting up gisbase, rcfile and dataDir

# if sys.platform == "linux" or sys.platform == "linux2":
#     rcfile = gsetup.init(gisbase, "/mnt/sda/grassdata/", "utm", "
garopaba_22J")
# elif sys.platform == "darwin":
#     rcfile = gsetup.init(gisbase, "/Volumes/MacintoshHD2/grassdat
a/", "utm", "garopaba_22J")
# elif platform ==
```

In [9]:
```
# requires version 7.8+
# create GRASS GIS runtime environment (mac and linux)
gisbase = subprocess.check_output(["grass79", "--config", "path"]).
strip().decode()
```

```
os.environ['GISBASE'] = gisbase
sys.path.append(os.path.join(gisbase, "etc", "python"))

# GRASS GIS imports
import grass.script as grass
import grass.script.setup as gsetup
import grass.script.array as garray
import grass.script.vector as gvect

# check GRASS version
# print(gisbase)
```

In [10]:
```
# set GRASS GIS session data
if sys.platform == "linux" or sys.platform == "linux2":
    rcfile = gsetup.init(gisbase, "/mnt/sda/grassdata/", "utm", "ga
ropaba_22J")
elif sys.platform == "darwin":
    rcfile = gsetup.init(gisbase, "/Volumes/MacintoshHD2/grassdata/
", "utm", "garopaba_22J")

# grass.message('Current GRASS GIS 7 environment:')
print (grass.gisenv())
```

```
{'GISDBASE': '/Volumes/MacintoshHD2/grassdata/', 'LOCATION_NAME':
'utm', 'MAPSET': 'garopaba_22J'}
```

In [11]:
```
# overwrite for GRASS modules
ow = True
```

In [12]:
```
# check region
# grass.parse_command('g.region', flags='pg')
# grass.run_command('g.region', flags='pg')
```

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Data directory

In [13]:
```
# Data dir
if sys.platform == "linux" or sys.platform == "linux2":
    dataDir = '/mnt/sda/Dropbox/USP/projetosPesquisa/LiDAR_terrestr
e_SfM/_areas_estudo/garopaba/DEMs_shapes'
elif sys.platform == "darwin":
    dataDir = '/Volumes/MacintoshHD2/Dropbox/USP/projetosPesquisa/L
iDAR_terrestre_SfM/_areas_estudo/garopaba/DEMs_shapes'


# point clouds dir
if sys.platform == "linux" or sys.platform == "linux2":
    pcDir = '/mnt/sda/geodata/pcs_garopaba'
elif sys.platform == "darwin":
    pcDir = '/Volumes/MacintoshHD2/_geodata/_dados_SPAMLab/garopaba
/pcs_garopaba'
```

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Data Import

Vector masks

ALS mask

In [14]:
```
# Entire dune field (polygon, manually digitized)
shp_als_mask = f'{dataDir}/mask_als_dunes.shp'
mask_als = 'mask_als'
```

TLS mask

In [15]:
```
# Dune field TLS area mask (polygon, manually digitized)
# import points in GRASS with r.in.xyz with 1m resolution, export a
s tiff, draw polygon in QGIS:
# g.region -pa res=01 w=732187 e=732674 n=6900302 s=6899889
# r.in.xyz --overwrite input=pcloud_tls_20mm.txt output=mdt_tls_201
9 method=mean separator=comma
# r.out.gdal --overwrite input=mdt_tls_2019@garopaba_22J output=pcl
oud_1m.tif format=GTiff
shp_tls_mask = f'{dataDir}/mask_tls.shp'
mask_tls = 'mask_tls'
```

SfM mask

In [16]:
```
# Dune field area mask (polygon, manually digitized)
shp_sfm_mask = f'{dataDir}/mask_sfm.shp'
mask_sfm = 'mask_sfm' # mask for clipping (pretty much the whole Sf
M area)
```

SfM + TLS mask

In [17]:
```
# import mask to constrain random points
# (excludes) vegetations and areas without TLS data
shp_tls_sfm = f'{dataDir}/mask_tls_sfm.shp'
mask_tls_sfm = 'mask_tls_sfm'
```

Volume mask

In [18]:
```
# area for volume calculation
shp_vol_mask = f'{dataDir}/mask_volume.shp'
mask_vol = 'mask_vol'
```

Import masks

In [19]:
```
grass.run_command('v.in.ogr', input=shp_als_mask, output=mask_als,
flags='o', overwrite=ow)
```

In [20]:
```
grass.run_command('v.in.ogr', input=shp_tls_mask, output=mask_tls,
flags='o', overwrite=ow)
```

In [21]:
```
grass.run_command('v.in.ogr', input=shp_sfm_mask, output=mask_sfm,
flags='o', overwrite=ow)
```

In [22]:
```
grass.run_command('v.in.ogr', input=shp_tls_sfm, output=mask_tls_sf
m, flags='o', overwrite=ow)
```

In [23]:
```
grass.run_command('v.in.ogr', input=shp_vol_mask, output=mask_vol,
flags='o', overwrite=ow)
```

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Airborne LiDAR data

Airborne LiDAR survey (2010-09, processed by Geoid ltda.)
This dataset is available via OpenTopography - http://dx.doi.org/10.5069/G9DN430Z (http://dx.doi.org/10.5069/G9DN430Z)

- Delivered in LAS format
- full point cloud: 12,319,797 points (area larger than dune field)

- first return points extract with LAStools
- first-return point cloud: 11,574,555 points (area larger than dune field)

- imported into GRASS as vector points
- clipped to a vector mask (commom area of SfM-MVS and ALS)
- resulting vector (pcloud_als): 2,380,005 points

In [24]:
```
# convert LAS to TXT (run this in a terminal):
# cd _path_to_your_files_
# using Martin Isenburg's LAStools with wine:
# wine _path_to_lastools_bin_/las2txt.exe -i Pontos_Garopaba.las -p
arse xyz -rescale 0.01 0.01 0.01 -first_only -o pcloud_als.txt
```

In [25]:
```
# ALS - names and files
pc_als_orig = 'pc_als_2010_orig'
pc_als = 'pc_als'
pc_als_txt = f'{pcDir}/pcloud_als.txt'
```

In [26]:
```
# import ALS data, clip to mask and remove original
grass.run_command('g.region', vector=mask_als, res=0.1, flags='pa')
grass.run_command('v.in.ascii', input=pc_als_txt, output=pc_als_ori
g, separator='space', x=1, y=2, z=3, flags='ztr', overwrite=ow)
grass.run_command('v.clip', input=pc_als_orig, output=pc_als, clip=
mask_sfm, overwrite=ow) # points: 2,380,005
grass.run_command('g.remove', type='vector', name=pc_als_orig, flag
s='f')
```

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SfM-MVS reconstruction of dune field

SfM-MVS survey 2019-02
This dataset is available via OpenTopography - http://dx.doi.org/10.5069/G9DV1H19 (http://dx.doi.org/10.5069/G9DV1H19)

- Exported from Agisoft Metashape as LAS
- Converted to TXT with LAStools
- full point cloud: 344,595,132 points

For comparison with TLS:

- imported into GRASS as mean value in each 10cm-pixel raster (r.in.xyz)
- clipped to a vector mask (TLS survey area)
- converted to vector for interpolation
- resulting vector (pc_sfm_rinxyz_avg10cm): 8,079,569 points

For comparison with ALS:

- thinned by every 125th point to be of similar size of the ALS point cloud after clipping
- imported into GRASS as vector points
- clipped to a vector mask (commom area of SfM-MVS and ALS)
- resulting vector (pc_sfm_t125): 2,378,399 points

Full-resolution point cloud (for comparison with TLS)

In [27]:
```
# convert LAS to TXT (run this in a terminal):
# cd _path_to_your_files_
# LAStools:
# wine _path_to_lastools_bin_/las2txt.exe -i pcloud_sfm.las -parse
xyz -rescale 0.001 0.001 0.001 -o pcloud_sfm_full.txt
```

In [28]:
```
# SfM - names and files
sfm_avg10cm = 'sfm_rinxyz_avg10cm'
pc_sfm_avg10cm = 'pc_sfm_rinxyz_avg10cm'
```

```
pc_sfm_tlsarea = f'{pcDir}/pcloud_sfm_full.txt'
```

In [29]:
```
# set region and mask
grass.run_command('g.region', vector=mask_tls, res=0.1, flags='pa')
grass.run_command('r.mask', vector=mask_tls, overwrite=ow)
```

In [30]:
```
# import as raster using 'mean' val in 10cm, fix null values
grass.run_command('r.in.xyz', input=pc_sfm_tlsarea, output=sfm_avg1
0cm, method='mean', separator='space', overwrite=ow)
grass.run_command('r.null', map=sfm_avg10cm, setnull=0)
```

In [31]:
```
# convert to vector for interpolation
grass.run_command('r.to.vect', input=sfm_avg10cm, output=pc_sfm_avg
10cm, type='point', flags='zt')
# grass.parse_command('v.info', map=sfm_mean)
# Number of points:       8,079,569
```

Thinned point cloud (for comparison with ALS)

In [32]:
```
# convert LAS to TXT and thin points (run this in a terminal):
# cd _path_to_your_files_
# LAStools:
# wine _path_to_lastools_bin_/las2txt.exe -i pcloud_sfm.las -parse
xyz -rescale 0.001 0.001 0.001 -keep_every_nth 125 -o pcloud_sfm_fu
ll_t125.txt
```

In [33]:
```
# SfM - names and files
pc_sfm_t125_orig = 'pc_sfm_t125_orig'
pc_sfm_t125 = 'pc_sfm_t125'
pc_sfm_t125_txt = f'{pcDir}/pcloud_sfm_t125.txt'
```

In [34]:
```
# import SfM data (thinned), clip to SfM mask and remove original v
ector
grass.run_command('g.region', vector=mask_sfm, res=0.1, flags='pa')
grass.run_command('v.in.ascii', input=pc_sfm_t125_txt, output=pc_sf
m_t125_orig, separator='space', x=1, y=2, z=3, flags='ztr', overwri
te=ow)
grass.run_command('v.clip', input=pc_sfm_t125_orig, output=pc_sfm_t
125, clip=mask_sfm, overwrite=ow) # points: 2,378,399
grass.run_command('g.remove', type='vector', name=pc_sfm_t125_orig,
flags='f')
```

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Terrestrial LiDAR

TLS survey 2019-02
This dataset is available via OpenTopography - [https://doi.org/10.5069/G9CN7228 (https://doi.org/10.5069/G9CN7228)](https://doi.org/10.5069/G9CN7228)

- Exported from FARO Scene as E57
- Converted to TXT with CloudCompare (in Windows, because E57 doesn't really work in other OS)
- Thinned in FARO Scene with 20mm minimum distance between points
- full point cloud: 170,141,709 points

- imported into GRASS as mean value in each 10cm-pixel raster (r.in.xyz)
- clipped to a vector mask (TLS survey area)
- converted to vector for interpolation
- resulting vector (pc_tls_rinxyz_avg10cm): 7,039,501 points

In [35]:
```
# TLS - names and files
tls_avg10cm = 'tls_rinxyz_avg10cm'
pc_tls_avg10cm = 'pc_tls_rinxyz_avg10cm'
pc_tls_txt = f'{pcDir}/pcloud_tls_20mm_utm.txt' #adjust to yours
```

In [36]:
```
# set region and mask
grass.run_command('g.region', vector=mask_tls, res=0.1, flags='pa')
grass.run_command('r.mask', vector=mask_tls, overwrite=ow)
```

In [37]:
```
# import as raster using 'mean' val in 10cm, fix null values
grass.run_command('r.in.xyz', input=pc_tls_txt, output=tls_avg10cm,
method='mean', separator='comma', overwrite=ow)
grass.run_command('r.null', map=tls_avg10cm, setnull=0)
```

In [38]:
```
# convert to vector for interpolation
grass.run_command('r.to.vect', input=tls_avg10cm, output=pc_tls_avg
10cm, type='point', flags='zt', overwrite=ow)
# grass.parse_command('v.info', map=tls_mean)
# Number of points:       7,039,501
```

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Maps of point density

Import point clouds as raster to create maps of point density/m2
See details of each point cloud processing in the folowwing sections

In [39]:
```
# remove any raster mask
grass.run_command('r.mask', flags='r')
```

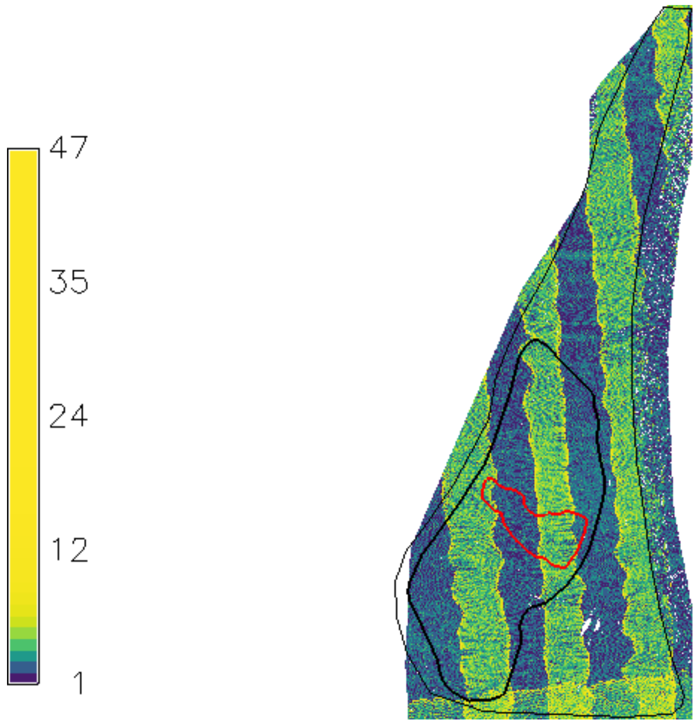
Airborne LiDAR density

In [40]:
```
# ALS
pc_als_txt = f'{pcDir}/pcloud_als.txt'
als_density = 'als_density'
grass.run_command('g.region', vector=mask_als, res=1, grow=10, flag
s='pa')
```

In [41]:
```
grass.run_command('r.in.xyz', input=pc_als_txt, output=als_density,
method='n', separator='space', overwrite=ow)
grass.run_command('r.null', map=als_density, setnull=0)
grass.run_command('r.colors', map=als_density, color='viridis', fla
gs='e')
```

In [43]:
```
# display with virtual monitor rendered to png
grass.run_command('d.mon', start='png', output='view.png', overwrit
e=ow)
grass.run_command('d.rast', map=als_density)
grass.run_command('d.vect', map=mask_als, fill_color='none', width=
1) #
grass.run_command('d.vect', map=mask_sfm, fill_color='none', width=
2) # SfM area in black
grass.run_command('d.vect', map=mask_tls, fill_color='none', color=
'red', width=2) # TLS area in red
grass.run_command('d.legend', raster=als_density, at='5,80,0,3', fl
ags='sf')
Image('view.png')
```

Out[43]:



In [44]:
```
grass.run_command('d.mon', stop='png')
```

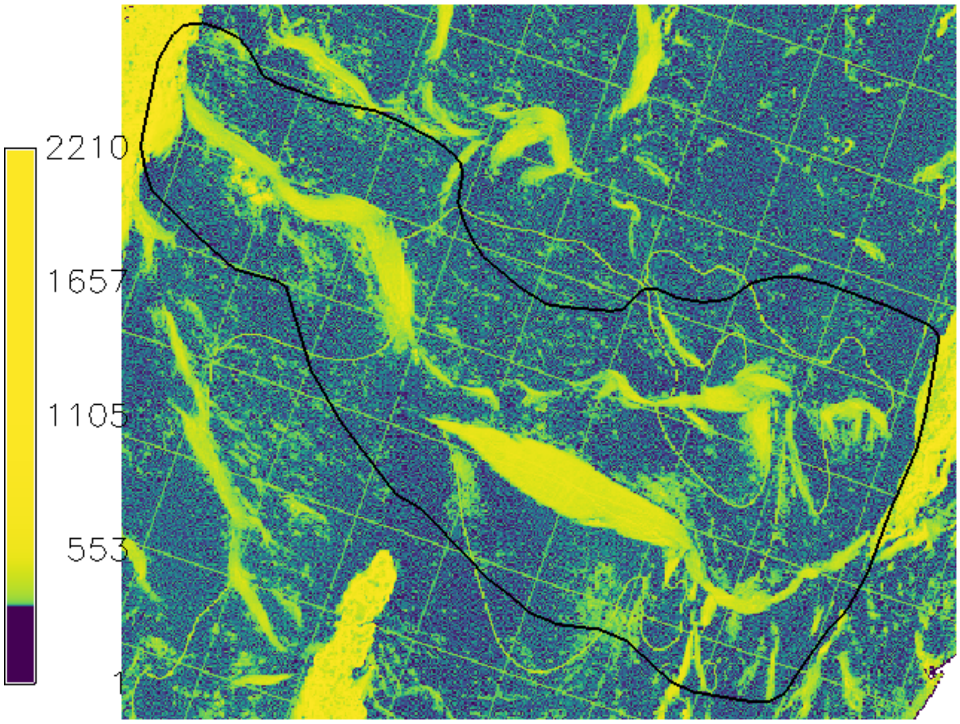
SfM - full resolution (TLS area) density

In [45]:
```
# SfM - full resolution
pc_sfm_tlsarea = f'{pcDir}/pcloud_sfm_full.txt'
sfm_full_density = 'sfm_tlsarea_fullres_density'
grass.run_command('g.region', vector=mask_tls, res=1, grow=10, flag
s='pa')
```

```
In [46]: grass.run_command('r.in.xyz', input=pc_sfm_tlsarea, output=sfm_full
_density, method='n', separator='space', overwrite=ow)
grass.run_command('r.null', map=sfm_full_density, setnull=0)
grass.run_command('r.colors', map=sfm_full_density, color='viridis'
, flags='e')
```

```
In [47]: # display with virtual monitor rendered to png
grass.run_command('d.mon', start='png', output='view.png', overwrit
e=ow)
grass.run_command('d.rast', map=sfm_full_density)
grass.run_command('d.vect', map=mask_tls, fill_color='none', width=
2, color='black') # TLS area in black
grass.run_command('d.legend', raster=sfm_full_density, at='5,80,0,3
', flags='sf')
Image('view.png')
```

Out[47]:




```
In [48]: grass.run_command('d.mon', stop='png')
```

SfM - thinned by 125th points (TLS area) density

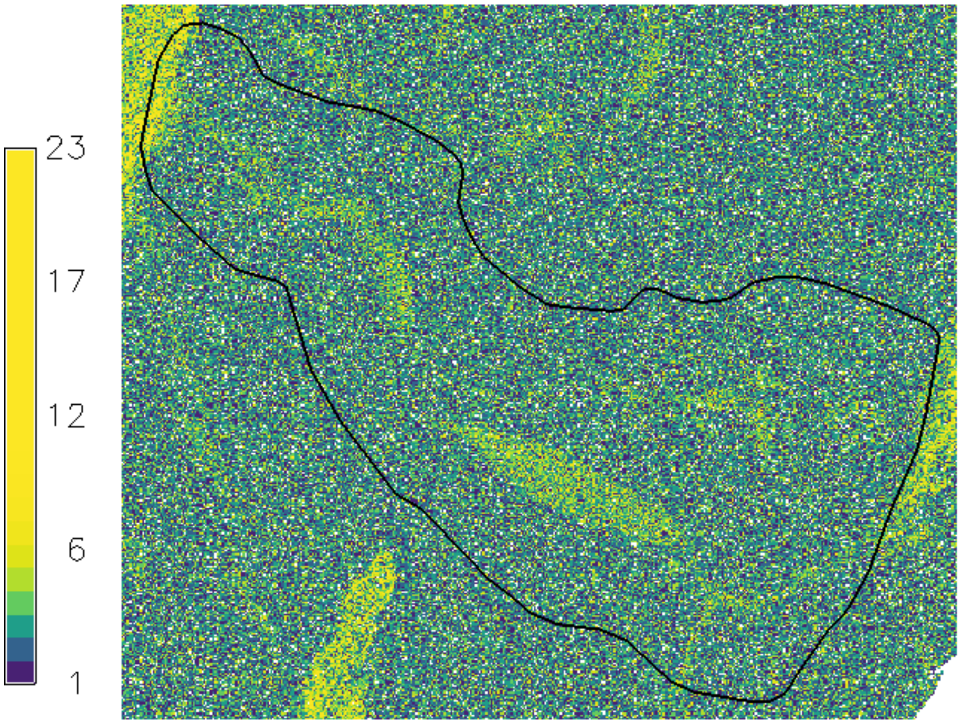
```
In [49]: # thinned by 125th points
pc_sfm_t125_txt = f'{pcDir}/pcloud_sfm_t125.txt' # adjust to yours
sfm_t125_density = 'sfm_t125_density'
grass.run_command('g.region', vector=mask_tls, res=1, grow=10, flag
s='pa')
```

```
In [50]: grass.run_command('r.in.xyz', input=pc_sfm_t125_txt, output=sfm_t12
5_density, method='n', separator='space', overwrite=ow)
grass.run_command('r.null', map=sfm_t125_density, setnull=0)
grass.run_command('r.colors', map=sfm_t125_density, color='viridis'
, flags='e')
```

```
In [51]: # display with virtual monitor rendered to png
```

```
grass.run_command('d.mon', start='png', output='view.png', overwrit
e=ow)
grass.run_command('d.rast', map=sfm_t125_density)
grass.run_command('d.vect', map=mask_tls, fill_color='none', width=
2, color='black') # TLS area in black
grass.run_command('d.legend', raster=sfm_t125_density, at='5,80,0,3
', flags='sf')
Image('view.png')
```

Out[51]:



In [52]:
```
grass.run_command('d.mon', stop='png')
```

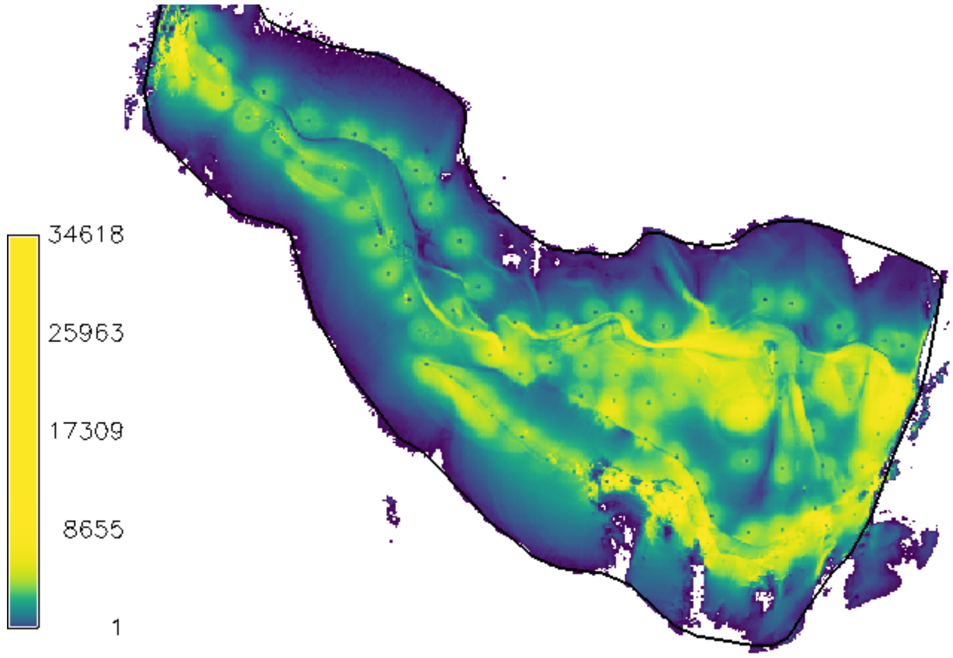
Terrestrial LiDAR density

In [53]:
```
# TLS
pc_tls_txt = f'{pcDir}/pcloud_tls_20mm_utm.txt' #adjust to yours
tls_density = 'tls_density'
grass.run_command('g.region', vector=mask_tls, res=1, grow=10, flag
s='pa')
```

In [54]:
```
grass.run_command('r.in.xyz', input=pc_tls_txt, output=tls_density,
method='n', separator='comma', overwrite=ow)
grass.run_command('r.null', map=tls_density, setnull=0)
grass.run_command('r.colors', map=tls_density, color='viridis', fla
gs='e')
```

In [55]:
```
# display with virtual monitor rendered to png
grass.run_command('d.mon', start='png', output='view.png', overwrit
e=ow)
grass.run_command('d.rast', map=tls_density)
grass.run_command('d.vect', map=mask_tls, fill_color='none', width=
2, color='black') # TLS area in black
grass.run_command('d.legend', raster=tls_density, at='5,60,0,3', fl
ags='sf')
Image('view.png')
```

Out[55]:



In [56]:
```
grass.run_command('d.mon', stop='png')
```

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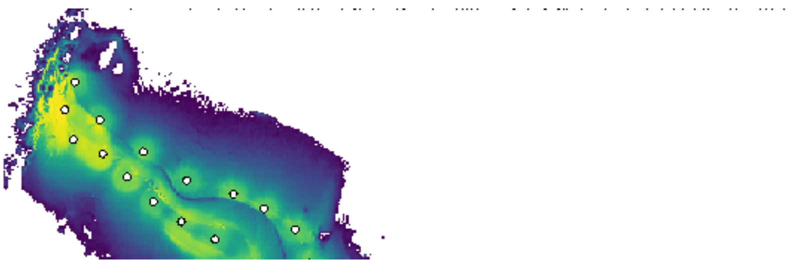
TLS scans positions

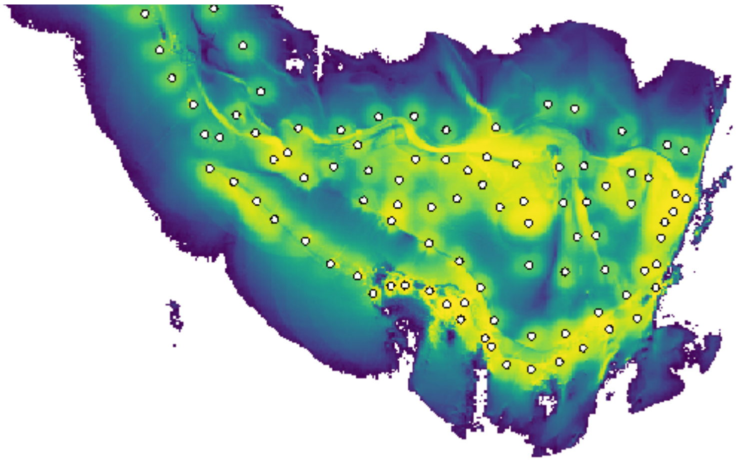
In [57]:
```
# import points
shp_scans = f'{dataDir}/scans_position.shp'
scans = 'scans_tls'
grass.run_command('v.in.ogr', input=shp_scans, output=scans, flags=
'o', overwrite=ow)
```

In [58]:
```
# set region
grass.run_command('g.region', vector=mask_tls, res=1, grow=10, flag
s='pa')
```

In [59]:
```
# display with virtual monitor rendered to png
grass.run_command('d.mon', start='png', output='view.png', overwrit
e=ow)
grass.run_command('d.rast', map=tls_density)
grass.run_command('d.vect', map=scans, fill_color='white', icon='ba
sic/circle') # TLS area in black
Image('view.png')
```

Out[59]:





In [60]:
```
grass.run_command('d.mon', stop='png')
```

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Comparison between Terrestrial LiDAR / SfM-MVS

Interpolate TLS and SfM DEMs, create shaded relief images

In [61]:
```
# settings for interpolation, shaded reliefs, names for the files
method='bilinear'
step = 0.5
altitude = 30
azimuth = 25
az_txt = f'{azimuth:>03.0f}' #'{:>03.0f}'.format(azimuth)

dem_tls_10cm = f'tls_rinxyz_avg10cm_{method}_step_{str(step)}'
dem_tls_10cm_shade = f'{dem_tls_10cm}_shade_{az_txt}_{str(altitude)
}'

dem_sfm_10cm = f'sfm_rinxyz_avg10cm_{method}_step_{str(step)}'
dem_sfm_10cm_shade = f'{dem_sfm_10cm}_shade_{az_txt}_{str(altitude)
}'

diff_sfm_tls_10cm = 'diff_10cm_sfm_tls'
diff_sfm_tls_10cm_shade = f'{diff_sfm_tls_10cm}_shade_{az_txt}_{str
(altitude)}'
```

In [62]:
```
# set region and mask
grass.run_command('g.region', vector=mask_tls, res=0.1, flags='pa')
grass.run_command('r.mask', vector=mask_tls, overwrite=ow)
```

In [63]:
```
# interpolate TLS - 10cm
grass.run_command('v.surf.bspline', input=pc_tls_avg10cm, raster_ou
tput=dem_tls_10cm, ew_step=step, ns_step=step, method=method, mask=
'MASK', overwrite=ow)
```

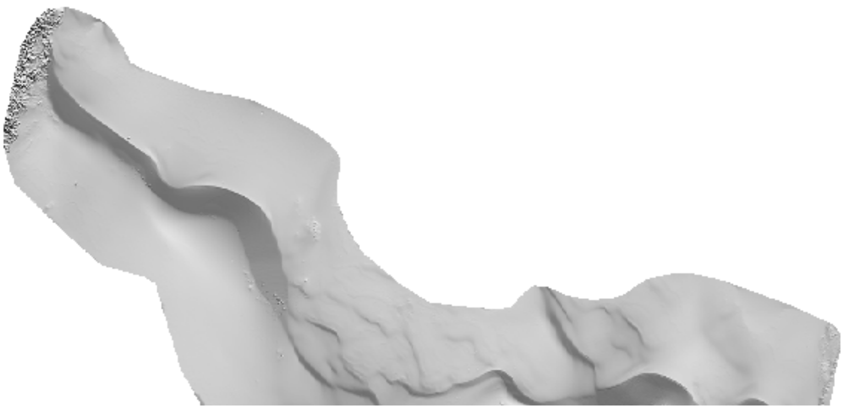
In [64]:
```
# interpolate SfM - 10cm
grass.run_command('v.surf.bspline', input=pc_sfm_avg10cm, raster_ou
tput=dem_sfm_10cm, ew_step=step, ns_step=step, method=method, mask=
'MASK', overwrite=ow)
```

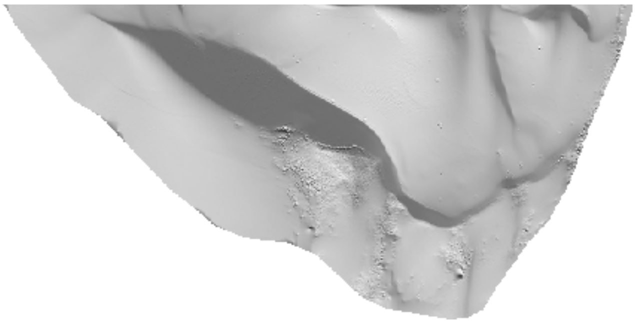
In [65]:
```
# DEM of Difference - SfM minus TLS
grass.mapcalc('${out} = ${sfm} - ${tls}',
    out=diff_sfm_tls_10cm,
    tls=dem_tls_10cm,
    sfm=dem_sfm_10cm,
    overwrite = True)
```

In [66]:
```
# make shaded reliefs and optionally export as tiff
# TLS
grass.run_command('r.relief', input=dem_tls_10cm, output=dem_tls_10
cm_shade, azimuth=azimuth, altitude=altitude, overwrite=ow)
# grass.run_command('r.out.gdal', input=dem_tls_shade, output=dem_t
ls_shade+'.tif', format='GTiff', type='Int16', overwrite=ow)

# SfM
grass.run_command('r.relief', input=dem_sfm_10cm, output=dem_sfm_10
cm_shade, azimuth=azimuth, altitude=altitude, overwrite=ow)
# grass.run_command('r.out.gdal', input=dem_sfm_5cm_shade, output=d
em_sfm_5cm_shade+'.tif', format='GTiff', type='Int16', overwrite=ow
)

# diff
grass.run_command('r.colors', map=diff_sfm_tls_10cm, color='differe
nces', flags='e')
grass.run_command('r.relief', input=diff_sfm_tls_10cm, output=diff_
sfm_tls_10cm_shade, azimuth=azimuth, altitude=altitude, overwrite=o
w)
# grass.run_command('r.out.gdal', input=diff_sfm_tls_shade, output=
diff_sfm_tls_shade+'.tif', format='GTiff', type='Int16', overwrite=
ow)
```

In [67]:
```
# TLS
# display with virtual monitor rendered to png
grass.run_command('d.mon', start='png', output='view.png', overwrit
e=ow)
grass.run_command('d.rast', map=dem_tls_10cm_shade)
Image('view.png')
```

Out[67]:

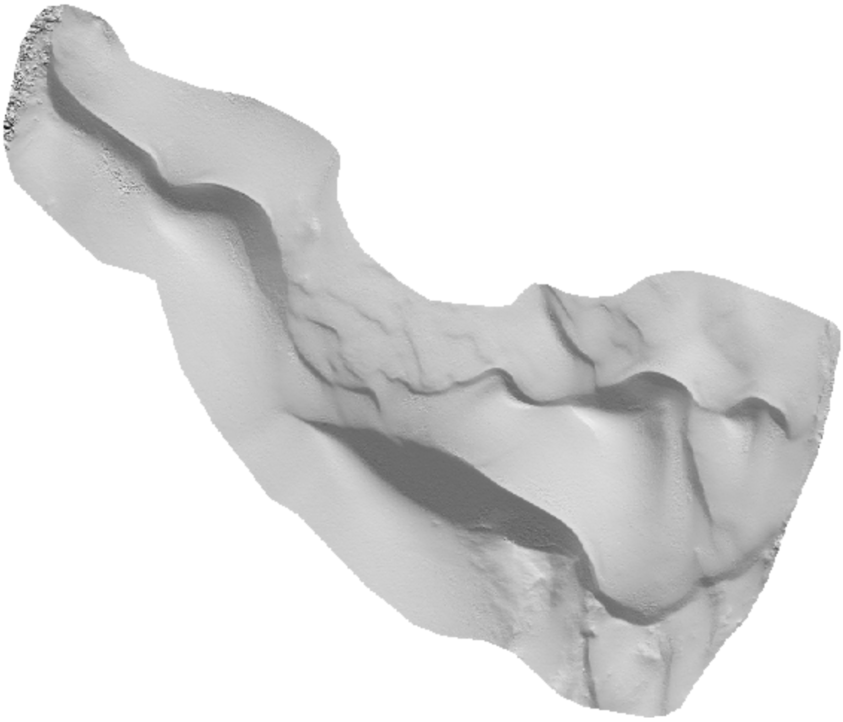




In [68]:
```
grass.run_command('d.mon', stop='png')
```

In [69]:
```
# SfM
# display with virtual monitor rendered to png
grass.run_command('d.mon', start='png', output='view.png', overwrit
e=ow)
grass.run_command('d.rast', map=dem_sfm_10cm_shade)
Image('view.png')
```

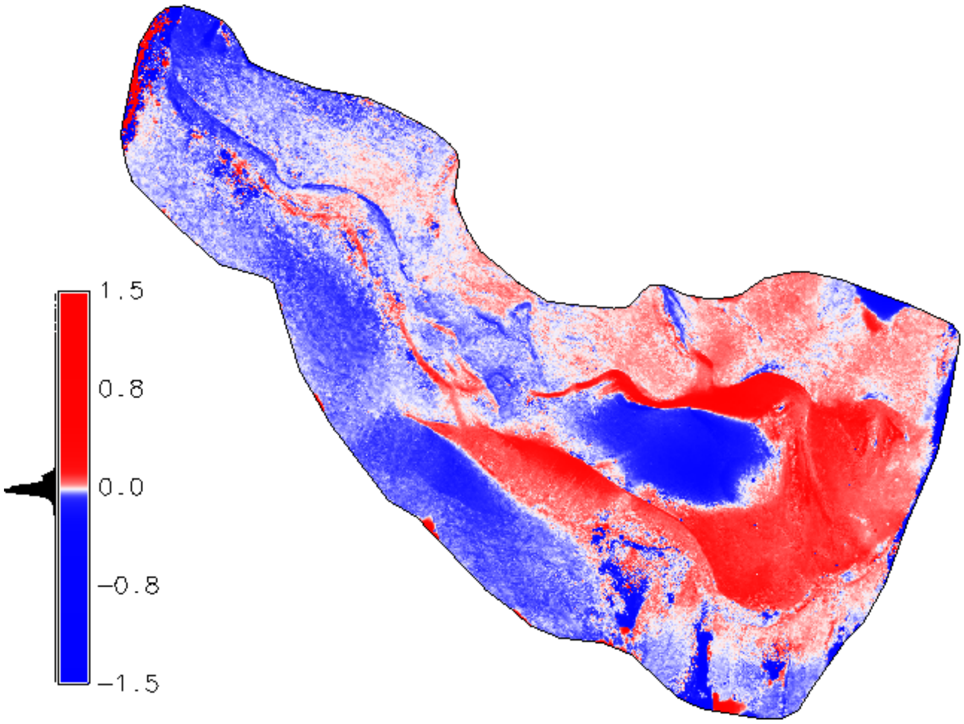
Out[69]:



In [70]:
```
grass.run_command('d.mon', stop='png')
```

In [71]:
```
# diff
# display with virtual monitor rendered to png
grass.run_command('d.mon', start='png', output='view.png', overwrit
e=ow)
grass.run_command('d.rast', map=diff_sfm_tls_10cm)
grass.run_command('d.vect', map=mask_tls, fill_color='none')
grass.run_command('d.legend', raster=diff_sfm_tls_10cm, at='5,60,5,
8', range='-1.5,1.5', flags='d')
Image('view.png')
Image('view.png')
```

Out[71]:



In [72]:
```
grass.run_command('d.mon', stop='png')
```

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Surface roughness

In [73]:
```
# set region and mask
mask_tls = 'mask_tls'
grass.run_command('g.region', vector=mask_tls, res=0.1, flags='pa')
grass.run_command('r.mask', vector=mask_tls, overwrite=ow)
```

In [74]:
```
# settings for roughness, names for the files
w = 5  # window size
op = 'stddev' # neighborhood operation

tls_slope = dem_tls_10cm + '_slope'
sfm_slope = dem_sfm_10cm + '_slope'

tls_rough = tls_slope + '_std_' + str(w) + 'x' + str(w)
sfm_rough = sfm_slope + '_std_' + str(w) + 'x' + str(w)
```

In [75]:
```
# slope
grass.run_command('r.slope.aspect', elevation=dem_tls_10cm, slope=t
ls_slope, overwrite=ow)
grass.run_command('r.slope.aspect', elevation=dem_sfm_10cm, slope=s
fm_slope, overwrite=ow)
```

In [76]:
```
# roughness
grass.run_command('r.neighbors', input=tls_slope, output=tls_rough,
method=op, size=w, overwrite=ow)
grass.run_command('r.neighbors', input=sfm_slope, output=sfm_rough,
method=op, size=w, overwrite=ow)
```

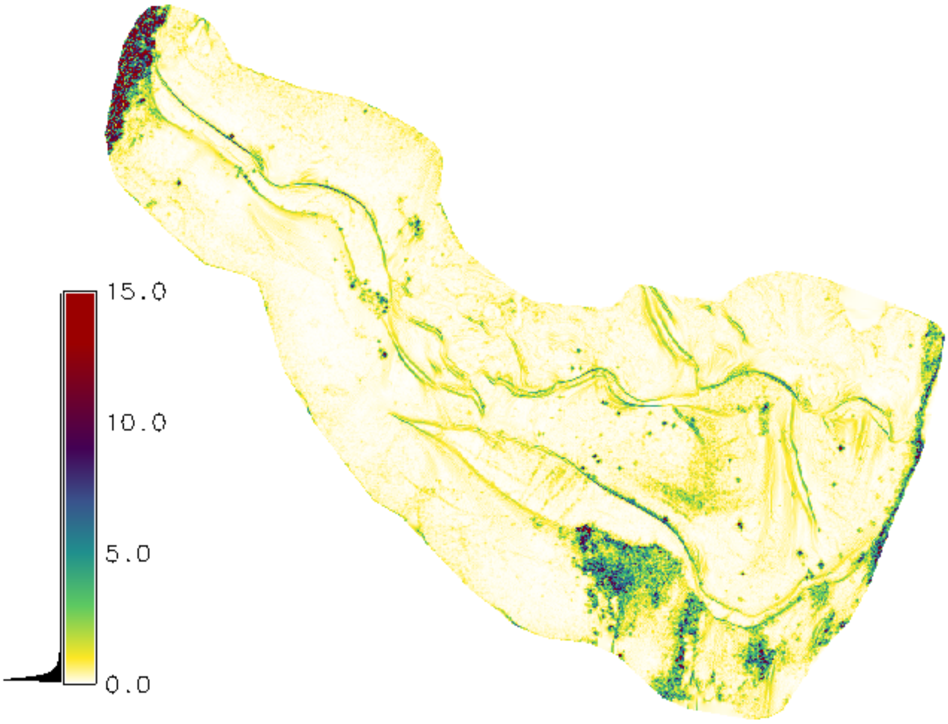
In [77]:
```
# set custom colortable, based on viridis
rules='''0 255:255:255
1 253:231:37
3 93:201:98
5 32:144:141
7 58:82:139
9 68:1:84
13 155:0:0
30 155:0:0
'''
# save rules to file
with open('rules.txt', 'w+') as file:
    file.write(rules)

grass.run_command('r.colors', map=tls_rough, rules='rules.txt')
grass.run_command('r.colors', map=sfm_rough, rules='rules.txt')
```

In [78]:
```
# display with virtual monitor rendered to png
grass.run_command('d.mon', start='png', output='view.png', overwrit
e=ow)
grass.run_command('d.rast', map=tls_rough)
grass.run_command('d.legend', raster=tls_rough, at='5,60,7,10', ran
```

```
ge='0,15', flags='sd', label_step=5)
Image('view.png')
```

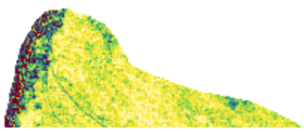
Out[78]:

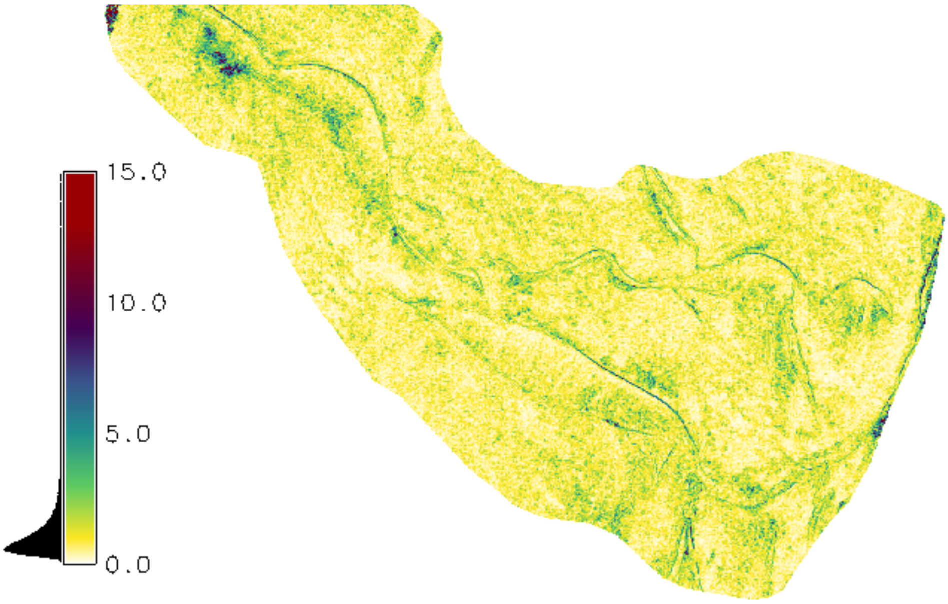


In [79]:
```
grass.run_command('d.mon', stop='png')
```

In [80]:
```
# display with virtual monitor rendered to png
grass.run_command('d.mon', start='png', output='view.png', overwrit
e=ow)
grass.run_command('d.rast', map=sfm_rough)
grass.run_command('d.legend', raster=sfm_rough, at='5,60,7,10', ran
ge='0,15', flags='sd', label_step=5)
Image('view.png')
```

Out[80]:






```
In [81]: grass.run_command('d.mon', stop='png')
```

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Noise reduction

Denoise analysis is in notebook *garopaba_als_sfm_tls_denoise_jupyter_python3.ipynb*

- FPDEMS algorithm
- tested different parameters combinations
- run FPD for SfM-MVS DEM (TLS area)
- imported FPD DEM bck to GRASS for comparison with TLS

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Stats, metrics (SfM x TLS)

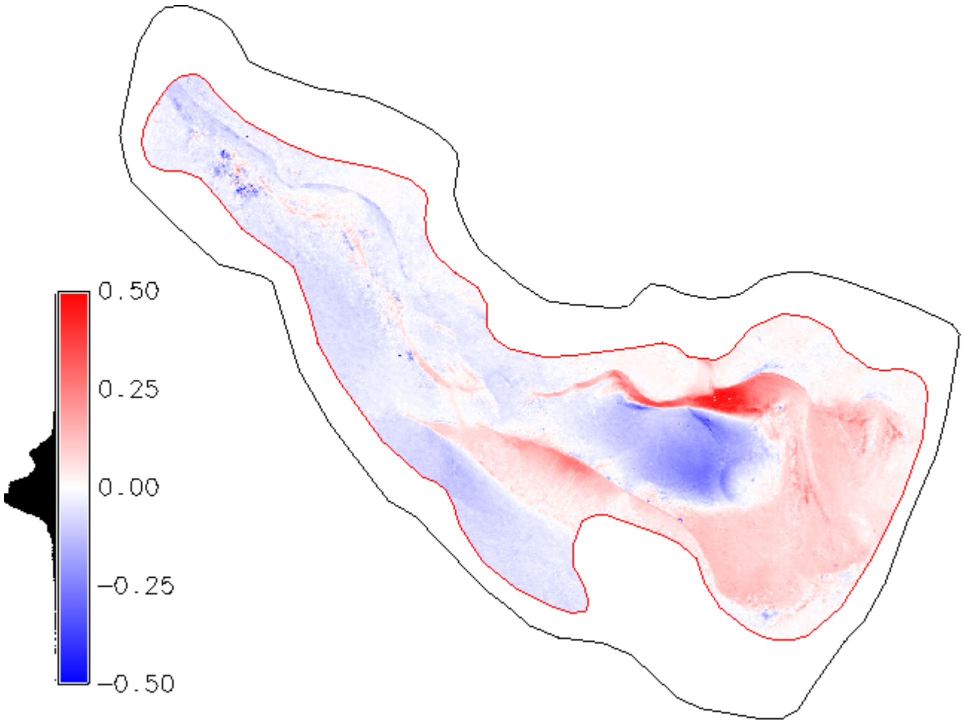
run stats and error metrics only for a sub-mask covering the areas without vegetation or interpolated voids in TLS

```
In [84]: # make new raster of diff only inside the inner mask, for legend di
         splay
         grass.run_command('r.mask', vector=mask_tls_sfm, overwrite=ow)
         diff_sfm_tls_10cm_clip = f'{diff_sfm_tls_10cm}_clip'
         grass.mapcalc('${out} = if(${dem},${dem},null())',
             out=diff_sfm_tls_10cm_clip,
             dem=diff_sfm_tls_10cm,
             overwrite = True)
         grass.run_command('r.colors', map=diff_sfm_tls_10cm_clip, color='di
```

```
fferences')
grass.run_command('r.mask', flags='r')
```

In [87]:
```
# display with virtual monitor rendered to png
grass.run_command('d.mon', start='png', output='view.png', overwrit
e=ow)
grass.run_command('d.rast', map=dem_tls_10cm_shade)
grass.run_command('d.rast', map=diff_sfm_tls_10cm_clip)
grass.run_command('d.vect', map=mask_tls, fill_color='none')
grass.run_command('d.vect', map=mask_tls_sfm, fill_color='none', co
lor='red') # mask for error analysis
grass.run_command('d.legend', raster=diff_sfm_tls_10cm_clip, at='5,
60,5,8', range='-0.5,1', flags='d')
Image('view.png')
```

Out[87]:



In [88]:
```
grass.run_command('d.mon', stop='png')
```

In [89]:
```
# set display format for stats
pd.set_option('display.float_format', lambda x: '%.3f' % x)
```

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Export DEMs (inside mask) as tiff - faster to read into pandas with rasterio

In [90]:
```
# set region and mask
mask_tls_sfm = 'mask_tls_sfm'
grass.run_command('g.region', vector=mask_tls_sfm, res=0.1, flags='
pa')
grass.run_command('r.mask', vector=mask_tls_sfm, overwrite=ow)
```

In [91]:
```
# FPD settings
k = 17
i = 5
```

```
t = 20
```

In [92]:
```
# files names
sfm_clip = f'{dataDir}/{dem_sfm_10cm}_clip.tif'
fpd_clip = f'{dataDir}/{dem_sfm_10cm}_full_fpd_i{i}_t{t}_k{k}_clip.
tif'
tls_clip = f'{dataDir}/{dem_tls_10cm}_clip.tif'
mask = f'{dataDir}/mask_tls_sfm.shp'
```

In [93]:
```
# export to dataDir
grass.run_command('r.out.gdal', input=dem_sfm_10cm, output=sfm_clip
, format='GTiff', overwrite=ow)
grass.run_command('r.out.gdal', input=dem_tls_10cm, output=tls_clip
, format='GTiff', overwrite=ow)
grass.run_command('r.out.gdal', input=sfm_fpd, output=fpd_clip, for
mat='GTiff', overwrite=ow)
```

In [94]:
```
# read into dataframe
sfm_fpd_tls = pd.DataFrame()

sfm = xr.open_rasterio(sfm_clip)
sfm_fpd_tls['sfm'] = sfm.to_series().dropna()

tls = xr.open_rasterio(tls_clip)
sfm_fpd_tls['tls'] = tls.to_series().dropna()

fpd = xr.open_rasterio(fpd_clip)
sfm_fpd_tls['fpd'] = fpd.to_series().dropna()
```

In [95]:
```
# diff cols
sfm_fpd_tls['diff_sfm_tls'] = sfm_fpd_tls['sfm'] - sfm_fpd_tls['tls
']
sfm_fpd_tls['diff_fpd_tls'] = sfm_fpd_tls['fpd'] - sfm_fpd_tls['tls
']
```

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Stats - all pixels

In [96]:
```
# calculate stats for each DEM
# could've used pd.describe() but I wanted skew and kurtosis
# also, I wanted the table with stats as columns
df_stats = pd.DataFrame(columns = ['min','max','mean','median','std
dev','skew','kurt','p25','p75'], index=['tls','sfm','fpd'])
for dem in ['tls','sfm','fpd','diff_sfm_tls','diff_fpd_tls']:
    rast_max = sfm_fpd_tls[dem].max()
    rast_min = sfm_fpd_tls[dem].min()
    rast_mean = sfm_fpd_tls[dem].mean()
    rast_median = sfm_fpd_tls[dem].quantile(q=0.50)
    rast_stddev = sfm_fpd_tls[dem].std()
    rast_p25 = sfm_fpd_tls[dem].quantile(q=0.25)
    rast_p75 = sfm_fpd_tls[dem].quantile(q=0.75)
    rast_skew = sfm_fpd_tls[dem].skew()
    rast_kurt = sfm_fpd_tls[dem].kurtosis()
```

```
    df_stats.loc[dem] = [rast_min,rast_max,rast_mean,rast_median,ra
st_stddev,rast_skew,rast_kurt,rast_p25,rast_p75]

df_stats
```

Out[96]:

	min	max	mean	median	stddev	skew	kurt	p25	p75
tls	8.490	36.172	23.937	24.753	6.519	-0.277	-0.750	18.708	28.712
sfm	8.440	36.153	23.938	24.774	6.531	-0.283	-0.754	18.691	28.713
fpd	8.445	36.152	23.938	24.774	6.532	-0.283	-0.754	18.691	28.713
diff_sfm_tls	-1.506	0.519	0.001	-0.008	0.085	0.701	4.801	-0.045	0.046
diff_fpd_tls	-1.510	0.509	0.001	-0.008	0.085	0.703	4.849	-0.045	0.046

In [97]:

```
# print(df_stats.to_latex(float_format="{:4.3f}".format))
# \begin{tabular}{llllllllll}
# \toprule
# {} &     min &     max &    mean & median & stddev &    skew &    kurt
&     p25 &     p75 \\
# \midrule
# tls            &  8.490 & 36.172 & 23.937 & 24.753 &  6.519 & -0.27
7 & -0.750 & 18.708 & 28.712 \\
# sfm            &  8.440 & 36.153 & 23.938 & 24.774 &  6.531 & -0.28
3 & -0.754 & 18.691 & 28.713 \\
# fpd            &  8.445 & 36.152 & 23.938 & 24.774 &  6.532 & -0.28
3 & -0.754 & 18.691 & 28.713 \\
# diff\_sfm\_tls & -1.506 &  0.519 &  0.001 & -0.008 &  0.085 &  0.
701 &  4.801 & -0.045 &  0.046 \\
# diff\_fpd\_tls & -1.510 &  0.509 &  0.001 & -0.008 &  0.085 &  0.
703 &  4.849 & -0.045 &  0.046 \\
# \bottomrule
# \end{tabular}
```

In [98]:

```
# how much of the TLS DEM is below the SfM one?
ss.percentileofscore(tuple(sfm_fpd_tls['diff_sfm_tls']),0)
```

Out[98]: 54.693422413199784

In [99]:

```
# number of pixels with values below -0.5m of difference between DE
Ms
```

In [100]:

```
# total pixels
pxs = len(sfm_fpd_tls['diff_sfm_tls'])
print(pxs)
```

4823836

In [101]:

```
# pixels with value below -0.5
below = sum((sfm_fpd_tls['diff_sfm_tls']< -0.5))
```

```
print(below)
```

312

In [102]:
```
# in percentage
(below*100)/pxs
```

Out[102]: 0.0064678815780636

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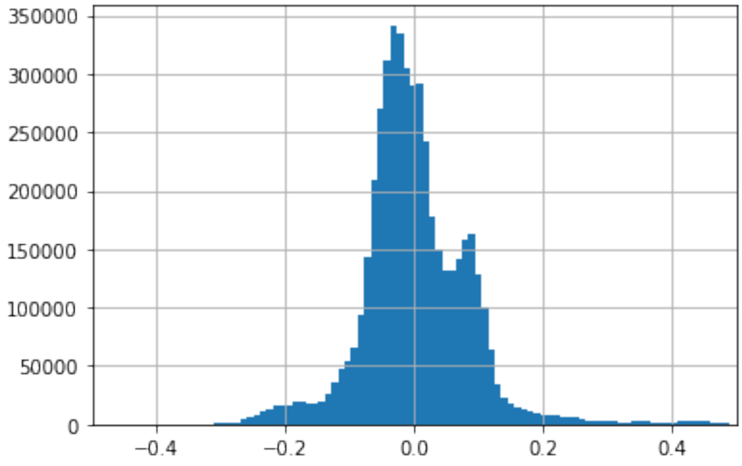
Graphics, errors (all pixels)

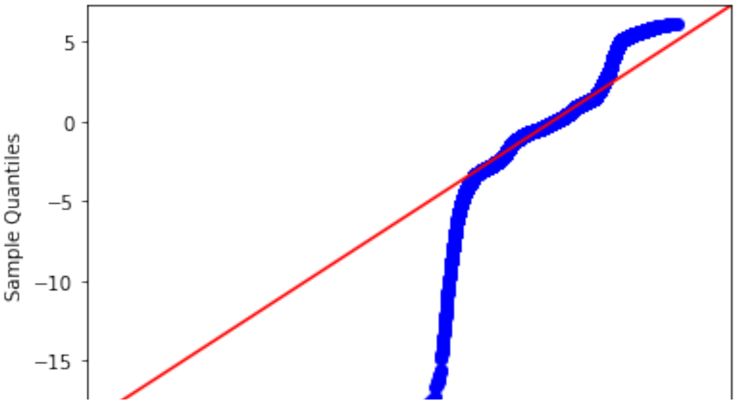
In [103]:
```
# histogram of differences (SfM minus TLS)
# FDR rule
print ('bins for diff: {:d}'.format(fdr(sfm_fpd_tls['diff_sfm_tls']
)))
# print (f'bins for diff: {fdr(sfm_tls['diff']):d}')
```

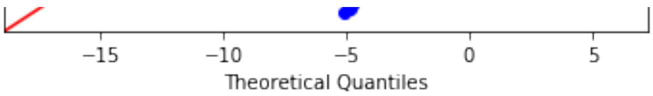
bins for diff: 1870

In [104]:
```
sfm_fpd_tls['diff_sfm_tls'].hist(bins=200)
plt.xlim(-0.5,0.5)
plt.savefig(f'{dataDir}/diff_hist.svg')
```



In [105]:
```
# QQ plot
qqplot(sfm_fpd_tls['diff_sfm_tls'],fit=True,line='45');
```



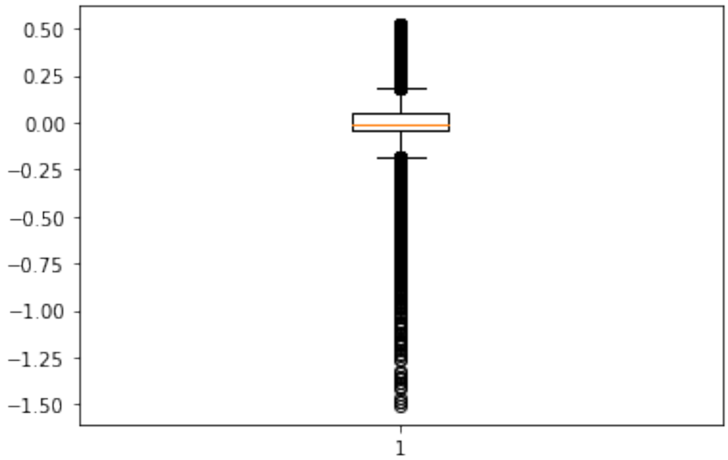


In [106]:
```
# Shapiro-Wilk normality test
stat, p = ss.shapiro(sfm_fpd_tls['diff_sfm_tls'])
print(f'Statistics={stat:.3f}, p={p:.3f}')
# interpret
alpha = 0.05
if p > alpha:
    print('Sample looks Gaussian (fail to reject H0)')
else:
    print('Sample does not look Gaussian (reject H0)')
```

```
Statistics=0.937, p=0.000
Sample does not look Gaussian (reject H0)

/Users/guano/.pyenv/versions/3.7.4/lib/python3.7/site-packages/sci
py/stats/morestats.py:1676: UserWarning: p-value may not be accura
te for N > 5000.
  warnings.warn("p-value may not be accurate for N > 5000.")
```

In [107]:
```
# boxplot
bp = plt.boxplot(sfm_fpd_tls['diff_sfm_tls'])
plt.savefig(f'{dataDir}/diff_boxplot.svg')
```



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Correlation (all pixels)

In [108]:
```
# TLS x interpolated SfM DEM
y = sfm_fpd_tls['tls']
x = sfm_fpd_tls['sfm']
slope, intercept, r_value, p_value, std_err = linregress(x, y)

# line_y = slope * x + intercept
# sfm_tls.plot.scatter(x='sfm',y='tls',c='diff',colormap='bwr')
# plt.plot(x, line_y, color="red")
# plt.savefig(f'{dataDir}/corrplot.svg')

print (f'slope = {slope:.4f}')
print (f'intercept = {intercept:.4f}')
print (f'r_value = {r_value:.4f}') # correlation coefficient
print (f'r_squared = {r_value**2:.4f}') # coefficient of determinat
ion
print (f'p_value = {p_value:.4f}')
print (f'std_err = {std_err:.4f}')
```

```
slope = 0.9980
intercept = 0.0476
r_value = 0.9999
r_squared = 0.9998
p_value = 0.0000
std_err = 0.0000
```

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MAE, RMSE (all pixels)

In [109]:
```
rmse_tls_sfm = err_rmse(sfm_fpd_tls['tls'],sfm_fpd_tls['sfm'])
mae_tls_sfm = err_mae(sfm_fpd_tls['tls'],sfm_fpd_tls['sfm'])

print (f'RMSE TLS x SfM: {rmse_tls_sfm:.3f}')
print (f'MAE TLS x SfM: {mae_tls_sfm:.3f}')
```

```
RMSE TLS x SfM: 0.085
MAE TLS x SfM: 0.061
```

In [110]:
```
rmse_tls_sfm = err_rmse(sfm_fpd_tls['tls'],sfm_fpd_tls['fpd'])
mae_tls_sfm = err_mae(sfm_fpd_tls['tls'],sfm_fpd_tls['fpd'])

print (f'RMSE TLS x SfM FPD: {rmse_tls_sfm:.3f}')
print (f'MAE TLS x SfM FPD: {mae_tls_sfm:.3f}')
```

```
RMSE TLS x SfM FPD: 0.085
MAE TLS x SfM FPD: 0.061
```

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Stats - random selection within dataframe

In [111]:
```
# select 200 values from dataframe
sfm_fpd_tls_rand = sfm_fpd_tls.sample(2000, random_state=123456)
```

In [112]:
```
# calculate stats for each DEM
# could've used pd.describe() but I wanted skew and kurtosis
# also, I wanted the table with stats as columns
df_stats = pd.DataFrame(columns = ['min','max','mean','median','std
dev','skew','kurt','p25','p75'], index=['tls','sfm','fpd'])
for dem in ['tls','sfm','fpd','diff_sfm_tls','diff_fpd_tls']:
    rast_max = sfm_fpd_tls_rand[dem].max()
    rast_min = sfm_fpd_tls_rand[dem].min()
    rast_mean = sfm_fpd_tls_rand[dem].mean()
    rast_median = sfm_fpd_tls_rand[dem].quantile(q=0.50)
    rast_stddev = sfm_fpd_tls_rand[dem].std()
    rast_p25 = sfm_fpd_tls_rand[dem].quantile(q=0.25)
    rast_p75 = sfm_fpd_tls_rand[dem].quantile(q=0.75)
    rast_skew = sfm_fpd_tls_rand[dem].skew()
    rast_kurt = sfm_fpd_tls_rand[dem].kurtosis()
    df_stats.loc[dem] = [rast_min,rast_max,rast_mean,rast_median,ra
st_stddev,rast_skew,rast_kurt,rast_p25,rast_p75]

df_stats
```

Out[112]:

	min	max	mean	median	stddev	skew	kurt	p25	p75
tls	8.526	36.023	24.015	24.840	6.455	-0.277	-0.725	18.863	28.639
sfm	8.483	35.990	24.010	24.830	6.468	-0.281	-0.730	18.822	28.654
fpd	8.477	35.989	24.010	24.826	6.468	-0.281	-0.729	18.824	28.654
diff_sfm_tls	-0.338	0.434	-0.004	-0.012	0.084	0.344	3.172	-0.048	0.041
diff_fpd_tls	-0.344	0.429	-0.004	-0.012	0.084	0.344	3.186	-0.048	0.042

In [113]:
```
# print(df_stats.to_latex(float_format="{:4.3f}".format))
# \begin{tabular}{llllllllll}
# \toprule
# {} &     min &     max &    mean & median & stddev &    skew &    kurt
&     p25 &     p75 \\
```

```
# \midrule
# tls           &  8.526 & 36.023 & 24.015 & 24.840 &  6.455 & -0.27
7 & -0.725 & 18.863 & 28.639 \\
# sfm           &  8.483 & 35.990 & 24.010 & 24.830 &  6.468 & -0.28
1 & -0.730 & 18.822 & 28.654 \\
# fpd           &  8.477 & 35.989 & 24.010 & 24.826 &  6.468 & -0.28
1 & -0.729 & 18.824 & 28.654 \\
# diff\_sfm\_tls & -0.338 &  0.434 & -0.004 & -0.012 &  0.084 &  0.
344 &  3.172 & -0.048 &  0.041 \\
# diff\_fpd\_tls & -0.344 &  0.429 & -0.004 & -0.012 &  0.084 &  0.
344 &  3.186 & -0.048 &  0.042 \\
# \bottomrule
# \end{tabular}
```

In [114]:

```
# how much of the TLS DEM is below the SfM one?
ss.percentileofscore(tuple(sfm_fpd_tls_rand['diff_sfm_tls']),0)
```

Out[114]:

```
56.45
```

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Graphics, errors (2000 pixels)

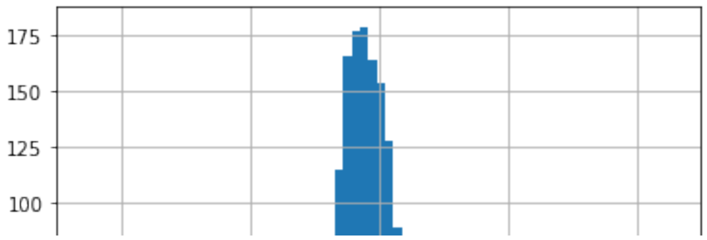
In [115]:

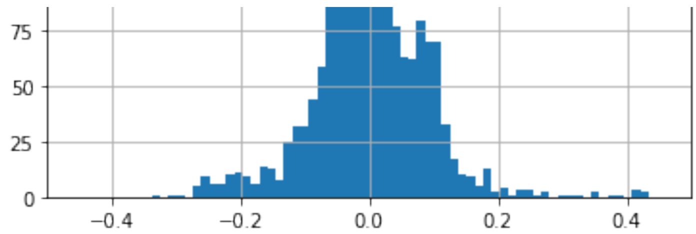
```
# histogram of differences (SfM minus TLS)
# FDR rule
print ('bins for diff: {:d}'.format(fdr(sfm_fpd_tls_rand['diff_sfm_
tls'])))
# print (f'bins for diff: {fdr(sfm_tls['diff']):d}')
```

```
bins for diff: 54
```

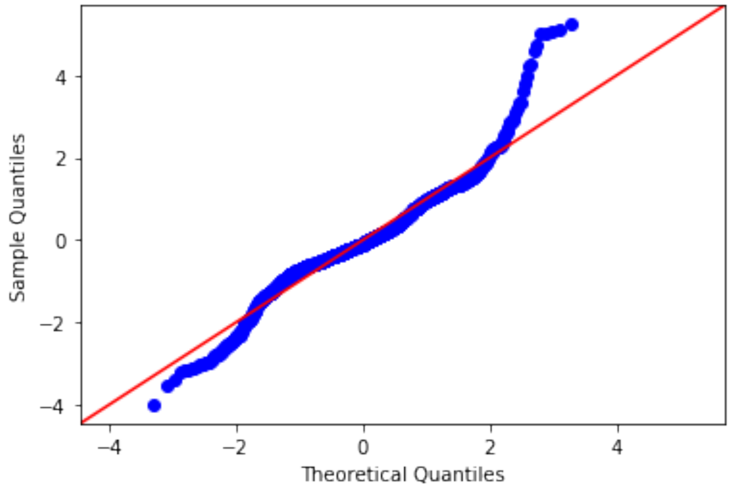
In [116]:

```
sfm_fpd_tls_rand['diff_sfm_tls'].hist(bins=60)
plt.xlim(-0.5,0.5)
plt.savefig(f'{dataDir}/diff_hist_rand.svg')
```





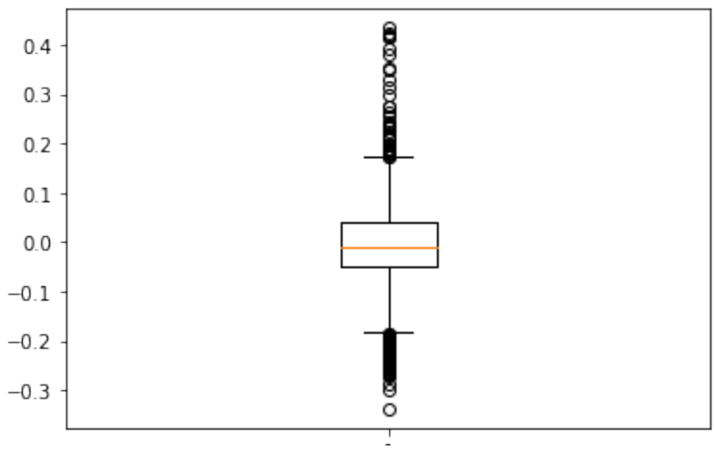
In [117]:
```
# QQ plot
qqplot(sfm_fpd_tls_rand['diff_sfm_tls'],fit=True,line='45');
```



In [118]:
```
# Shapiro-Wilk normality test
stat, p = ss.shapiro(sfm_fpd_tls_rand['diff_sfm_tls'])
print(f'Statistics={stat:.3f}, p={p:.3f}')
# interpret
alpha = 0.05
if p > alpha:
    print('Sample looks Gaussian (fail to reject H0)')
else:
    print('Sample does not look Gaussian (reject H0)')
```

```
Statistics=0.954, p=0.000
Sample does not look Gaussian (reject H0)
```

In [119]:
```
# boxplot
bp = plt.boxplot(sfm_fpd_tls_rand['diff_sfm_tls'])
plt.savefig(f'{dataDir}/diff_boxplot_rand.svg')
```



1

In [120]:
```
# number of outliers
len(bp['fliers'][0]._y)
```
Out[120]:
```
102
```

In [121]:
```
# whiskers y_val
[item.get_ydata()[1] for item in bp['whiskers']]
```
Out[121]:
```
[-0.18203375254299203, 0.17420957653028069]
```

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Correlation (2000 pixels)

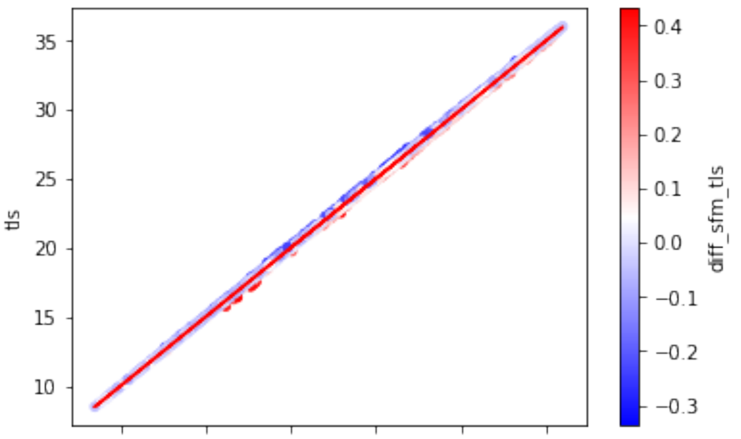
In [122]:
```
# TLS x interpolated SfM DEM
y = sfm_fpd_tls_rand['tls']
x = sfm_fpd_tls_rand['sfm']
slope, intercept, r_value, p_value, std_err = linregress(x, y)

line_y = slope * x + intercept
sfm_fpd_tls_rand.plot.scatter(x='sfm',y='tls',c='diff_sfm_tls',colo
rmap='bwr')
plt.plot(x, line_y, color="red")
plt.savefig(f'{dataDir}/corrplot_rand.svg')

print (f'slope = {slope:.4f}')
print (f'intercept = {intercept:.4f}')
print (f'r_value = {r_value:.4f}') # correlation coefficient
print (f'r_squared = {r_value**2:.4f}') # coefficient of determinat
ion
print (f'p_value = {p_value:.4f}')
print (f'std_err = {std_err:.4f}')
```

```
slope = 0.9980
intercept = 0.0520
r_value = 0.9999
r_squared = 0.9998
p_value = 0.0000
```

std_err = 0.0003



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MAE, RMSE (2000 pixels)

In [123]:
```
rmse_tls_sfm = err_rmse(sfm_fpd_tls_rand['tls'],sfm_fpd_tls_rand['s
fm'])
mae_tls_sfm = err_mae(sfm_fpd_tls_rand['tls'],sfm_fpd_tls_rand['sfm
'])

print (f'RMSE TLS x SfM: {rmse_tls_sfm:.3f}')
print (f'MAE TLS x SfM: {mae_tls_sfm:.3f}')
```

```
RMSE TLS x SfM: 0.084
MAE TLS x SfM: 0.061
```

In [124]:
```
rmse_tls_sfm = err_rmse(sfm_fpd_tls_rand['tls'],sfm_fpd_tls_rand['f
pd'])
mae_tls_sfm = err_mae(sfm_fpd_tls_rand['tls'],sfm_fpd_tls_rand['fpd
'])

print (f'RMSE TLS x SfM FPD: {rmse_tls_sfm:.3f}')
print (f'MAE TLS x SfM FPD: {mae_tls_sfm:.3f}')
```

```
RMSE TLS x SfM FPD: 0.084
MAE TLS x SfM FPD: 0.061
```

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Comparison between Airborne LiDAR / SfM-MVS

Interpolate ALS and SfM DEMs, create shaded relief images

In [125]:

```
# settings for interpolation, shaded reliefs, name the files, set mask
method='bilinear'
step = 2
altitude = 30
azimuth = 25
az_txt = f'{azimuth:>03.0f}'

dem_als = f'als_50cm_{method}_step_{str(step)}'
dem_als_shade = f'{dem_als}_shade_{az_txt}_{str(altitude)}'

dem_sfm = f'sfm_50cm_{method}_step_{str(step)}'
dem_sfm_shade = f'{dem_sfm}_shade_{az_txt}_{str(altitude)}'

diff_sfm_als = 'diff_sfm_minus_als'
dem_diff_shade = f'{diff_sfm_als}_shade_{az_txt}_{str(altitude)}'

# set region (0.5m resolution 3D) and mask
n = 6900951.5
s = 6899231.5
w = 731859.0
e = 732783.5
grass.run_command('g.region', n=n,s=s,w=w,e=e,t=60,b=0, res3=0.5, flags='p3a', save='dunes_default', overwrite=ow)
grass.run_command('r.mask', vector=mask_sfm, overwrite=ow)
# grass.run_command('r.mask', flags='r')
```

In [126]:

```
# Interpolate ALS
grass.run_command('v.surf.bspline', input=pc_als, raster_output=dem_als, ew_step=step, ns_step=step, method=method, mask='MASK', overwrite=ow)
```

In [127]:

```
# Interpolate SfM
grass.run_command('v.surf.bspline', input=pc_sfm_t125, raster_output=dem_sfm, ew_step=step, ns_step=step, method=method, mask='MASK', overwrite=ow)
```

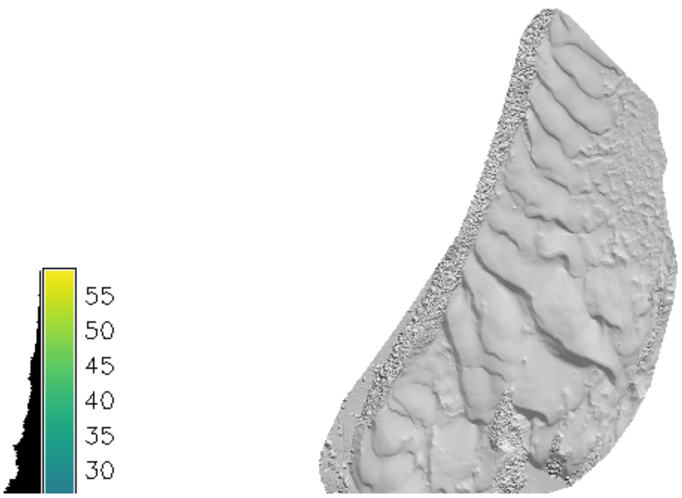
```
overwrite=ow)
```

In [128]:
```
# DEM of Difference - ALS (2010) minus SfM (2019)
grass.mapcalc('${out} = ${sfm} - ${als}',
    out=diff_sfm_als,
    als=dem_als,
    sfm=dem_sfm,
    overwrite = True)
```

In [129]:
```
# make shaded reliefs and optionally export as tiff
# ALS
grass.run_command('r.relief', input=dem_als, output=dem_als_shade,
azimuth=azimuth, altitude=altitude, overwrite=ow)
# grass.run_command('r.out.gdal', input=dem_als_shade, output=dem_a
ls_shade+'.tif', format='GTiff', type='Int16')
# SfM
grass.run_command('r.relief', input=dem_sfm, output=dem_sfm_shade,
azimuth=azimuth, altitude=altitude, overwrite=ow)
# grass.run_command('r.out.gdal', input=dem_sfm_shade, output=dem_s
fm_shade+'.tif', format='GTiff', type='Int16')
# diff
grass.run_command('r.colors', map=diff_sfm_als, color='differences'
)
grass.run_command('r.relief', input=diff_sfm_als, output=dem_diff_s
hade, azimuth=azimuth, altitude=altitude, overwrite=ow)
# grass.run_command('r.out.gdal', input=dem_diff_shade, output=dem_
diff_shade+'.tif', format='GTiff', type='Int16')
```

In [130]:
```
# display with virtual monitor rendered to png
grass.run_command('d.mon', start='png', output='view.png', overwrit
e=ow)
grass.run_command('d.rast', map=dem_als_shade)
grass.run_command('d.legend', raster=dem_als, at='5,60,7,10', range
='0,60', flags='sd', label_step=5)
Image('view.png')
```

Out[130]:



In [131]:
```
grass.run_command('d.mon', stop='png')
```

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Stats, histograms

In [132]:
```
# files names
als_tif = f'{dataDir}/{dem_als}.tif'
sfm_tif = f'{dataDir}/{dem_sfm}.tif'
```

In [133]:
```
# export to dataDir
grass.run_command('r.out.gdal', input=dem_als, output=als_tif, form
at='GTiff', overwrite=ow)
grass.run_command('r.out.gdal', input=dem_sfm, output=sfm_tif, form
at='GTiff', overwrite=ow)
```

In [134]:
```
# read into dataframe
df_dems = pd.DataFrame()

sfm = xr.open_rasterio(sfm_tif)
df_dems['sfm'] = sfm.to_series().dropna()

als = xr.open_rasterio(als_tif)
df_dems['als'] = als.to_series().dropna()
```

In [135]:
```
# diff col
df_dems['dod'] = df_dems['sfm'] - df_dems['als']
```

In [136]:
```
# option - use numpy to read DEM from GRASS (requires aux func, but
not xarray)
# read DSMs as arrays and create dataframe
# df_dems = pd.DataFrame()
# df_dems['als'] = raster_as_array(dem_als)
# df_dems['sfm'] = raster_as_array(dem_sfm)
# df_dems['dod'] = raster_as_array(diff_sfm_als)
```

In [137]:
```
# calculate stats for each DEM
# could've used pd.describe() but I wanted skew and kurtosis as wel
l
df_stats = pd.DataFrame(columns = ['min','max','mean','median','std
dev','skew','kurt','p25','p75'], index=['als','sfm','dod'])
for dem in ['als','sfm','dod']:
    rast_max = df_dems[dem].max()
    rast_min = df_dems[dem].min()
    rast_mean = df_dems[dem].mean()
    rast_median = df_dems[dem].quantile(q=0.50)
    rast_stddev = df_dems[dem].std()
    rast_p25 = df_dems[dem].quantile(q=0.25)
    rast_p75 = df_dems[dem].quantile(q=0.75)
    rast_skew = df_dems[dem].skew()
    rast_kurt = df_dems[dem].kurtosis()
    df_stats.loc[dem] = [rast_min,rast_max,rast_mean,rast_median,ra
st_stddev,rast_skew,rast_kurt,rast_p25,rast_p75]

df_stats
```

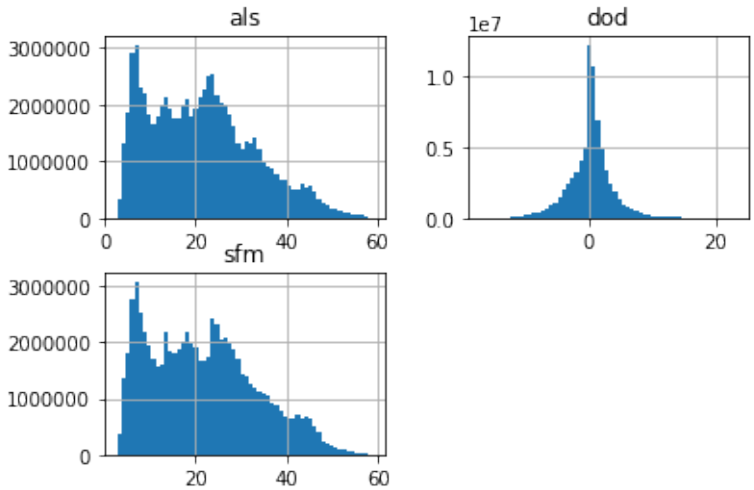
Out[137]:

	min	max	mean	median	stddev	skew	kurt	p25	p75
als	2.691	58.883	21.336	20.649	11.593	0.506	-0.411	11.644	28.769
sfm	2.888	58.625	21.643	20.668	11.659	0.447	-0.574	11.635	29.397
dod	-16.950	23.153	0.307	0.392	3.476	0.156	2.772	-1.259	1.799

In [138]:
```
# # export stats to latex
# print(df_stats.to_latex(float_format="{:4.2f}".format))
# \begin{tabular}{llllllllll}
# \toprule
# {} &    min &    max &  mean & median & stddev & skew &  kurt &
p25 &   p75 \\
# \midrule
# als &   2.69 & 58.88 & 21.34 &  20.65 &  11.59 & 0.51 & -0.41 & 1
1.64 & 28.77 \\
# sfm &   2.89 & 58.63 & 21.64 &  20.67 &  11.66 & 0.45 & -0.57 & 1
1.63 & 29.40 \\
# dod & -16.95 & 23.15 &  0.31 &   0.39 &   3.48 & 0.16 &  2.77 & -
1.26 &  1.80 \\
# \bottomrule
# \end{tabular}
```

In [139]:
```
# quick histograms, bins=60 as this is the approx range of elevation
df_dems.hist(bins=60)
```

Out[139]:
```
array([[<matplotlib.axes._subplots.AxesSubplot object at 0x1cb9af790>,
        <matplotlib.axes._subplots.AxesSubplot object at 0x1cb7e3710>],
       [<matplotlib.axes._subplots.AxesSubplot object at 0x1cb75f990>,
        <matplotlib.axes._subplots.AxesSubplot object at 0x1cb4b7790>]],
      dtype=object)
```



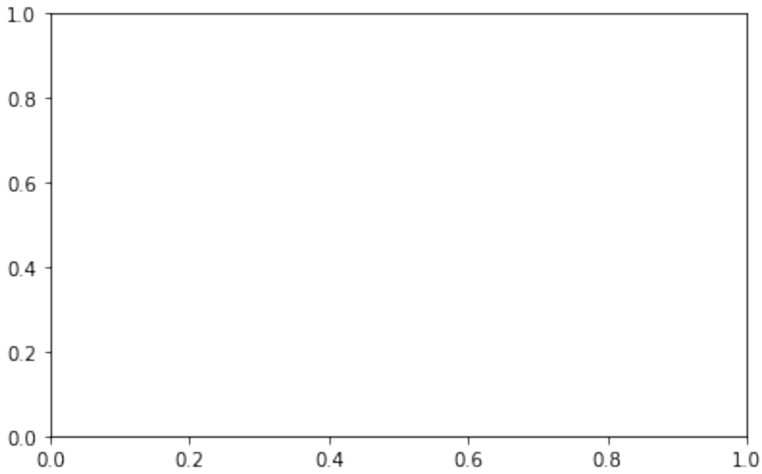
In [140]:
```
# use Freedman–Diaconis rule to calculate optimal bin size? -- TOO MUCH
print (f'bins for ALS: {fdr(df_dems.als):d}')
print (f'bins for SfM: {fdr(df_dems.sfm):d}')
print (f'bins for DoD: {fdr(df_dems.dod):d}')
```

```
bins for ALS: 689
bins for SfM: 658
bins for DoD: 2753
```

In [141]:
```
# make individual histograms and save as svg (in dataDir)
def do_hist(dem,nbins,out_dir):
    '''make histograms, save as svg in out_dir'''
    fileOut = f'{dataDir}/hist_{dem}.svg'
```

```
    df_dems[dem].hist(bins=nbins, label=dem)
    plt.title('Elevation histogram, '+ dem)
    plt.xlabel('Elevation')
    plt.ylabel('Cell count')
    plt.legend()
    plt.tight_layout()
    plt.savefig(fileOut)
    plt.clf()
    plt.cla()

# will use same number of bins for ALS and SfM
figDir = '.'
do_hist('als',nbins=60,out_dir=figDir)
do_hist('sfm',nbins=60,out_dir=figDir)
do_hist('dod',nbins=40,out_dir=figDir)
# an empty plot will be displayed, not sure why
```



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Volume calculation with r.volume and r3.stats

In [142]:
```
mask_vol = 'mask_vol'
grass.run_command('g.region', vector=mask_vol, res=0.5, tbres=0.1,
flags='pa3')
```

ALS LiDAR

In [143]:
```
# make raster of mask_vol
grass.run_command('v.to.rast', input=mask_vol, output=mask_vol, use
='val', overwrite=True)
```

In [144]:
```
# r.volume
# here we use the 'mask_vol' raster as a clump raster to sum the vo
lume of each cell
als_rvol_txt = grass.read_command('r.volume', input=dem_als, clump=
mask_vol)
```

```
# print(als_rvol_txt)

# Volume report on data from <als_50cm_bilinear_step_2> using clump
s on <mask_vol> raster map

# Category   Average   Data   # Cells        Centroid              T
otal
# Number      in clump  Total  in clump   Easting      Northing     V
olume
# ------------------------------------------------------------------
------------
#         1      24.08  36140462 1500908   732324.75   6900039.25
9035115.45
# ------------------------------------------------------------------
------------
#                                                   Total Volume =
9035115.45
```

SfM DEM

In [145]:

```
# r.volume
sfm_rvol_txt = grass.read_command('r.volume',input=dem_sfm, clump=m
ask_vol)

# print (sfm_rvol_txt)

# Volume report on data from <sfm_50cm_bilinear_step_2> using clump
s on <mask_vol> raster map

# Category   Average   Data   # Cells        Centroid              T
otal
# Number      in clump  Total  in clump   Easting      Northing     V
olume
# ------------------------------------------------------------------
------------
#         1      24.01  36043380 1500908   732324.75   6900039.25
9010844.95
# ------------------------------------------------------------------
------------
#                                                   Total Volume =
9010844.95
```

In [146]:

```
# difference
diff_rvol = grass.read_command('r.volume',input=diff_sfm_als, clump
=mask_vol)

# print(diff_rvol)

# Volume report on data from <diff_sfm_minus_als> using clumps on <
mask_vol> raster map

# Category   Average   Data   # Cells        Centroid              T
otal
# Number      in clump  Total  in clump   Easting      Northing     V
olume
# ------------------------------------------------------------------
------------
#         1      -0.06    -97082 1500908   732324.75   6900039.25
-24270.50
```

In [147]:
```
100-9010844.95*100/9035115.45
```
Out[147]:
```
0.2686241269888825
```
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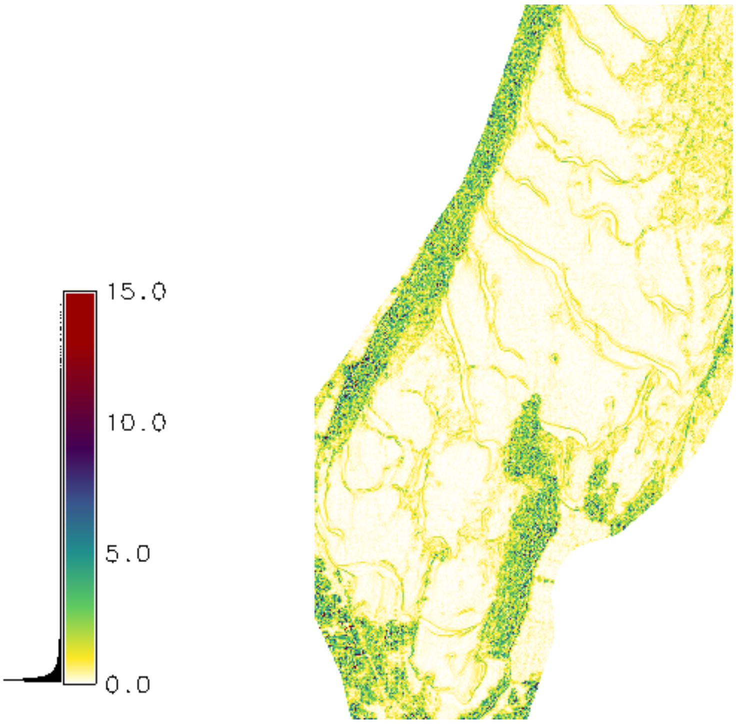
Displacement of dune crests

first calculate surface roughness of ALS and SfM DEMs

In [148]:
```
# settings for roughness, names for the files
w = 5  # window size
op = 'stddev' # neighborhood operation

als_slope = f'{dem_als}_slope'
sfm_slope = f'{dem_sfm}_slope'

als_rough = f'{als_slope}_std_{w}x{w}'
sfm_rough = f'{sfm_slope}_std_{w}x{w}'
```
In [149]:
```
# slope
grass.run_command('r.slope.aspect', elevation=dem_als, slope=als_sl
ope, overwrite=ow)
grass.run_command('r.slope.aspect', elevation=dem_sfm, slope=sfm_sl
ope, overwrite=ow)
```
In [150]:
```
# roughness
grass.run_command('r.neighbors', input=als_slope, output=als_rough,
method=op, size=w, overwrite=ow)
grass.run_command('r.neighbors', input=sfm_slope, output=sfm_rough,
method=op, size=w, overwrite=ow)
```
In [151]:
```
# set custom colortable, based on viridis
rules='''0 255:255:255
1 253:231:37
3 93:201:98
5 32:144:141
7 58:82:139
9 68:1:84
13 155:0:0
30 155:0:0
'''
# save rules to file
with open('rules.txt', 'w+') as file:
    file.write(rules)

grass.run_command('r.colors', map=als_rough, rules='rules.txt')
grass.run_command('r.colors', map=sfm_rough, rules='rules.txt')
```

In [152]:
```
# display with virtual monitor rendered to png
grass.run_command('d.mon', start='png', output='view.png', overwrit
e=ow)
grass.run_command('d.rast', map=als_rough)
grass.run_command('d.legend', raster=als_rough, at='5,60,7,10', ran
ge='0,15', flags='sd', label_step=5)
Image('view.png')
```

Out[152]:



In [153]:
```
grass.run_command('d.mon', stop='png')
```

In [154]:
```
# show detail of roughness map with dune crest
```

In [155]:
```
# import crests shapefiles
shp_crests_als = f'{dataDir}/crests_als_2010.shp'
als_crests = 'crests_als_2010'

shp_crests_sfm = f'{dataDir}/crests_sfm_2019.shp'
sfm_crests = 'crests_sfm_2019'
```

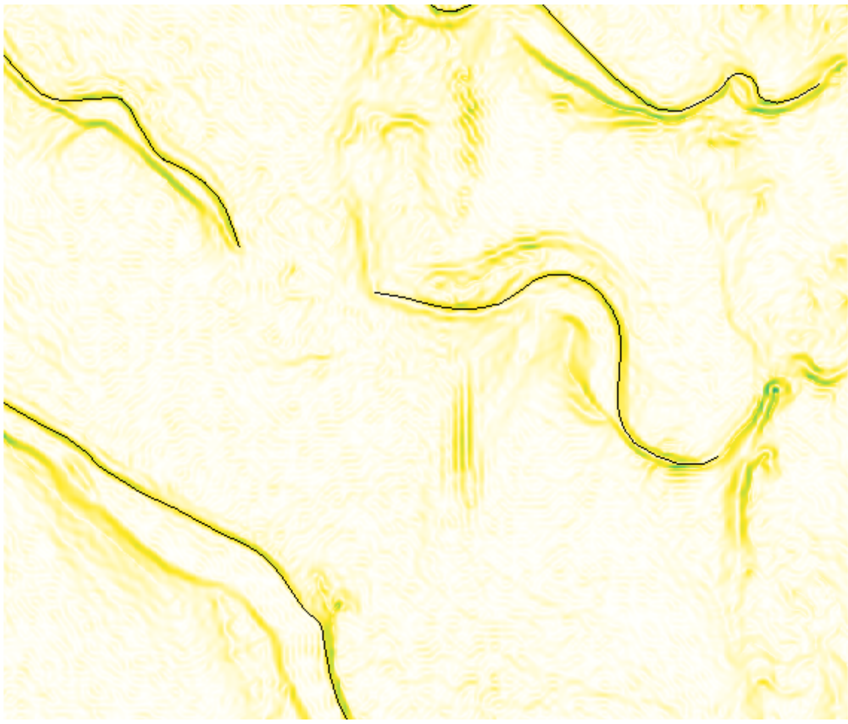
In [156]:
```
grass.run_command('v.in.ogr', input=shp_crests_als, output=als_cres
ts, flags='o', overwrite=ow)
grass.run_command('v.in.ogr', input=shp_crests_sfm, output=sfm_cres
ts, flags='o', overwrite=ow)
```

In [157]:
```
# set region
n = 6900380
s = 6900160
w = 732290
e = 732550
grass.run_command('g.region', n=n,s=s,w=w,e=e)
```

In [158]:
```
# display with virtual monitor rendered to png
grass.run_command('d.mon', start='png', output='view.png', overwrit
e=ow)
grass.run_command('d.rast', map=als_rough)
grass.run_command('d.vect', map=als_crests, color='black')
# grass.run_command('d.legend', raster=als_rough, at='5,60,7,10', r
ange='0,15', flags='sd', label_step=5)
```

```
Image('view.png')
```

Out[158]:



In [159]:
```
grass.run_command('d.mon', stop='png')
```

displacement of crests

In [160]:
```
# displacement lines file
shp_lin = f'{dataDir}/displacement_crests_2010_2019.shp'
```

In [162]:
```
# azimuth and length are calculated by functions in 'azim_p3.py'
azim, leng = azim_p3.azim(shp_lin)
```

```
Linear features in file: 164

len azimuth: 164
```

In [163]:
```
# put azim, length in dataframe
df_lin = pd.DataFrame(columns=['az','len'])
```

In [164]:
```
df_lin['az'] = azim
df_lin['len'] = leng
```

In [165]:
```
df_lin.describe()
```

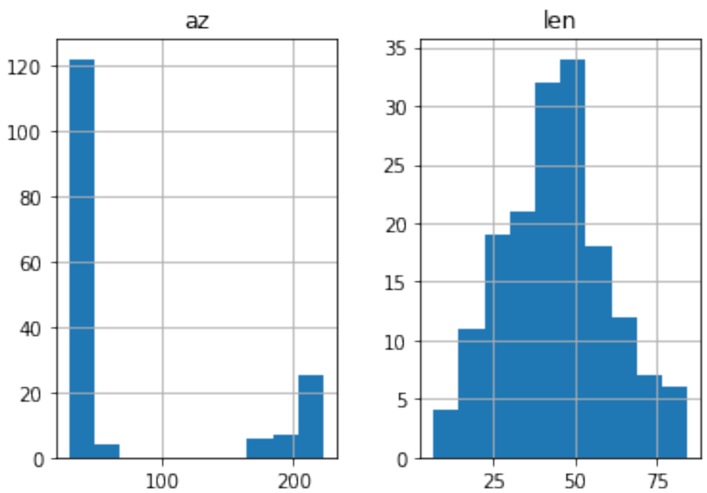
Out[165]:

	az	len
count	164.000	164.000
mean	77.134	44.337
std	71.472	16.624
min	28.301	6.590
25%	36.812	32.311
50%	38.973	44.780
75%	48.272	53.506

max	223.285	84.346

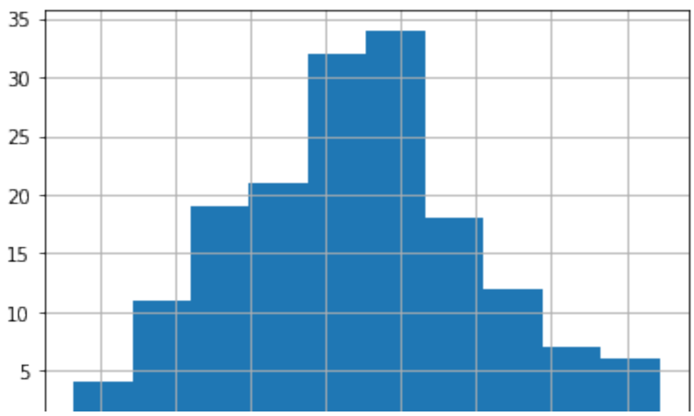
In [166]:
```
df_lin.hist()
```

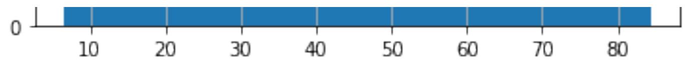
Out[166]:
```
array([[<matplotlib.axes._subplots.AxesSubplot object at 0x276adb2
10>,
        <matplotlib.axes._subplots.AxesSubplot object at 0x276b27d
d0>]],
      dtype=object)
```



In [167]:
```
# nbins with Freedman-Diaconis rule
nbins = fdr(df_lin['len'])
df_lin['len'].hist(bins=nbins)
```

Out[167]:
```
<matplotlib.axes._subplots.AxesSubplot at 0x276c47090>
```

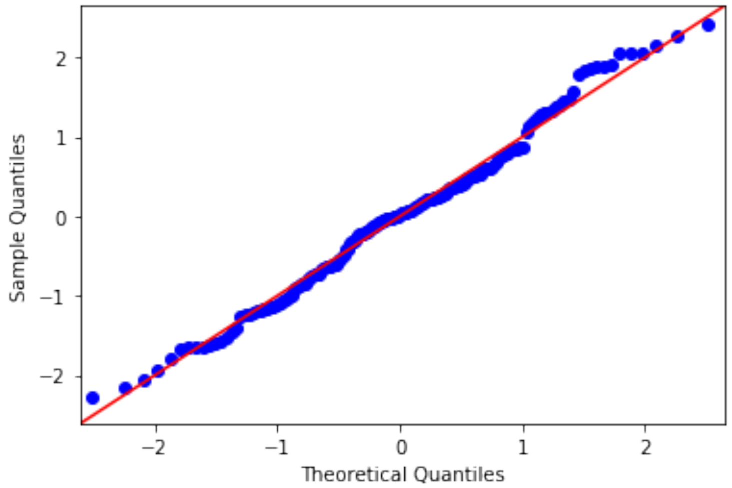




In [168]:
```
# Normality tests for displacement length
# https://machinelearningmastery.com/a-gentle-introduction-to-norma
lity-tests-in-python/
```

In [169]:
```
data = df_lin['len']
```

In [170]:
```
# QQ plot
qqplot(data,fit=True,line='45');
```



In [171]:
```
# Shapiro-Wilk Test
# from scipy.stats import shapiro
# normality test
stat, p = ss.shapiro(data)
print(f'Statistics={stat:.3f}, p={p:.3f}')
# interpret
alpha = 0.05
if p > alpha:
        print('Sample looks Gaussian (fail to reject H0)')
else:
        print('Sample does not look Gaussian (reject H0)')
```

```
Statistics=0.988, p=0.153
Sample looks Gaussian (fail to reject H0)
```

In [172]:
```
# D'Agostino's K^2 Test
# from scipy.stats import normaltest
stat, p = ss.normaltest(data)
print(f'Statistics={stat:.3f}, p={p:.3f}')
# interpret
alpha = 0.05
if p > alpha:
        print('Sample looks Gaussian (fail to reject H0)')
else:
        print('Sample does not look Gaussian (reject H0)')
```

```
Statistics=1.055, p=0.590
Sample looks Gaussian (fail to reject H0)
```

In [173]:
```
# Anderson-Darling Test
# from scipy.stats import anderson
# normality test
result = ss.anderson(data)
print(f'Statistic: {result.statistic:.3f}')
p = 0
for i in range(len(result.critical_values)):
        sl, cv = result.significance_level[i], result.critical_valu
es[i]
        if result.statistic < result.critical_values[i]:
                print(f'{sl:.3f}: {cv:.3f}, data looks normal (fail
to reject H0)')
        else:
                print(f'{sl:.3f}: {cv:.3f}, data does not look norm
al (reject H0)')
```

```
Statistic: 0.554
15.000: 0.563, data looks normal (fail to reject H0)
10.000: 0.641, data looks normal (fail to reject H0)
5.000: 0.769, data looks normal (fail to reject H0)
2.500: 0.897, data looks normal (fail to reject H0)
1.000: 1.067, data looks normal (fail to reject H0)
```

In [174]:
```
# from scipy.stats import kstest
ss.kstest(data, 'lognorm', args=(1,))
```

Out[174]:
```
KstestResult(statistic=0.9780098475326018, pvalue=2.66969373241490
05e-272)
```

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Azimuth analysis

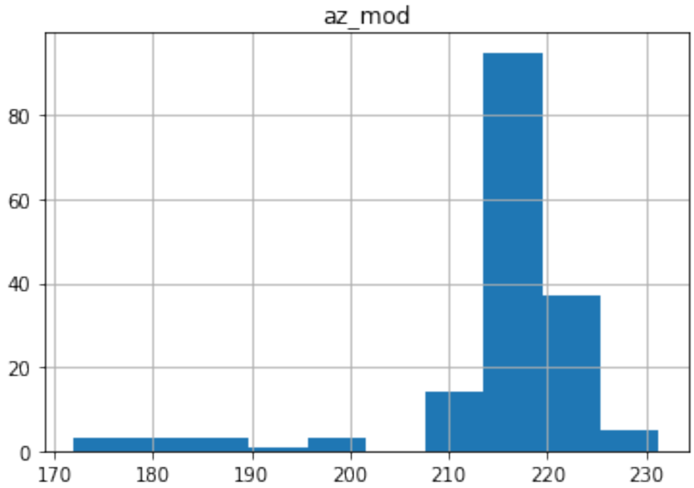
In [175]:
```
# Looking at the histogram, we see that the azimuth
# of displacement lines are clustered in the NE and SW quadrants.
# Since azimuth is calculated from the endpoints of lines,
# we get both quadrants depending on how teh line was drawn.
# The dune field migrates southward, so we need to convert
# the azimuth values to south quadrants (SE, SW)
azimMod = []
for az in df_lin['az']:
    if 0.0 < az <= 90.0: # NE quadrant
        azimMod.append(az + 180.0)
    elif 270.0 <= az <= 360.0: # NW quadrant
        azimMod.append(az + 180.0)
    else:
        azimMod.append(az)
```

In [176]:

```
# make a dataframe just to plot the histogram easily
az_m = pd.DataFrame(azimMod, columns =['az_mod'])
az_m.hist()
```

Out[176]:

```
array([[<matplotlib.axes._subplots.AxesSubplot object at 0x276c856
10>]],
      dtype=object)
```



In [177]:

```
# calculate mean direction
# from Fisher 1993, Statistical Analyis of circular data, p.31
az_rad = np.deg2rad(azimMod)
sinTheta = np.sin(az_rad)
cosTheta = np.cos(az_rad)
C = np.sum(cosTheta)
S = np.sum(sinTheta)

ThetaBar = np.arctan2(C,S)
ThetaBarDeg = np.rad2deg(ThetaBar)
```

In [178]:

```
# convert from arctan2 degrees to azimuth
# (note: modulo 360 does not work for this)
# https://stackoverflow.com/a/25398191/4984000
if ThetaBarDeg > 90.0:
    ThetaBarDeg = 450.0 - ThetaBarDeg
else:
    ThetaBarDeg = 90.0 - ThetaBarDeg
```

In [179]:

```
# mean direction of dune displacement
ThetaBarDeg
```

Out[179]: 215.55194503485

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Topographic profiles

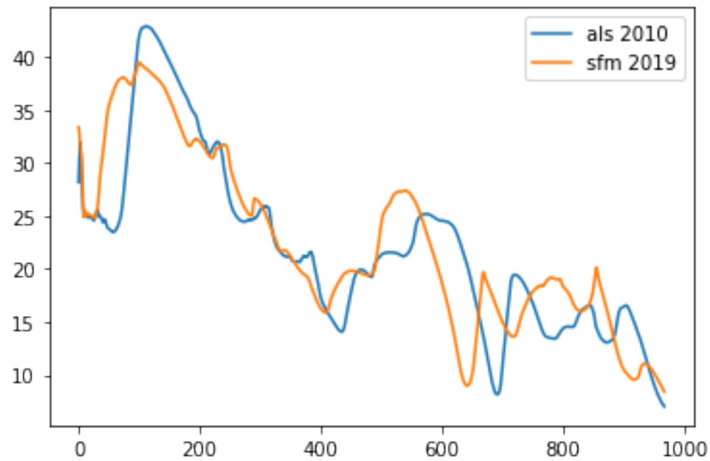
In [180]:
```
coords=(732000,6899600,732470,6900445)
```

In [183]:
```
grass.run_command('g.region', region='dunes_default', overwrite=ow)
```

In [184]:
```
# ALS
p_als = grass.read_command('r.profile', input=dem_als , output='-',
coordinates=coords, res=0.5, null='*')
p_als_x = p_als.split()[0::2]
p_als_y = p_als.split()[1::2]
als_x=[float(num) for num in p_als_x]
als_y=[float(num) for num in p_als_y]
```

In [185]:
```
# SfM
p_sfm = grass.read_command('r.profile', input=dem_sfm , output='-',
coordinates=coords, res=0.5, null='*')
p_sfm_x = p_sfm.split()[0::2]
p_sfm_y = p_sfm.split()[1::2]
sfm_x=[float(num) for num in p_sfm_x]
sfm_y=[float(num) for num in p_sfm_y]
```

In [186]:
```
# plot
plt.plot(als_x,als_y,label='als 2010')
plt.plot(sfm_x,sfm_y,label='sfm 2019')
plt.legend()
# save svg
fig = f'{dataDir}/topo_profiles_als_sfm.svg'
plt.savefig(fig)
```



In [187]:
```
# end GRASS GIS session
os.remove(rcfile)
```

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In [ ]:

In [ ]: