Workshop on Quantitative Geomorphology

Bodo Bookhagen, University of Potsdam

Schedule

Monday, 17.02.2020
- Introduction to Digital Elevation Model analysis
- Exercises with Python using snythetic and real-world DEMs
- Resampling and gridding artifacts
- Comparing slope and hypsometry of Earth and Mars, exploring 2D histograms
- Flow Direction and Flowaccumulation calculation

Tuesday, 18.02.2020
- Introduction to Landscape Evolution Modeling (LEM) using landlab
- Some simple modeling exercises using planes and Gaussian Hills
- Fault scarp modeling
- River-network Exercises

Schedule

Wednesday, 19.02.2020
- Introduction of Matlab TopoToolbox
- Exercises in the computer lab: relief, steepness indices, identifying knick points, chi analysis

Thursday, 19.02.2020
- Introduction to Lidar and SfM Point Cloud (PC) analysis
- PC analysis, visualization and classification using open-source tools
- Shape detection on PC data
- gridding of PC data to DEMs and generating your own high-resolution DEMs

Friday, 19.02.2020
- Using a Terrestrial Lidar scanner to generate your own point Cloud

Sharing Information

https://github.com/BodoBookhagen/QuantitativeGeomorphology_IITGn

Sharing Information

Monday, 17.02.2020

- Introduction to Digital Elevation Model analysis
- Exercises with Python using snythetic and real-world DEMs
- Resampling and gridding artifacts
- Comparing slope and hypsometry of Earth and Mars, exploring 2D histograms
- Flow Direction and Flowaccumulation calculation

Tuesday, 18.02.2020

- Introduction to Landscape Evolution Modeling (LEM) using landlab
- Some simple modeling exercises using planes and Gaussian Hills
- Fault scarp modeling
- River-network Exercises

Wednesday, 19.02.2020

- Introduction of Matlab TopoToolbox
- Exercises in the computer lab: relief, steepness indices, identifying knick points, chi analysis

Thursday, 19.02.2020

- Introduction to Lidar and SfM Point Cloud (PC) analysis
- PC analysis, visualization and classification using open-source tools
- Shape detection on PC data
- gridding of PC data to DEMs and generating your own high-resolution DEMs

Friday, 19.02.2020

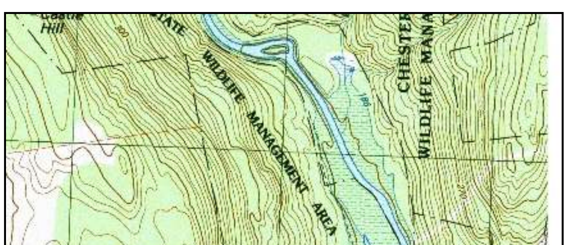
- Using a Terrestrial Lidar scanner to generate your own point Cloud
- Examples and Exercises from the Himalaya

Digital Elevation Models

Bodo Bookhagen, University of Potsdam

Applications of DEMs I

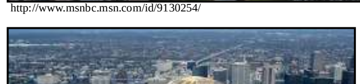
Which Way Does the Water Flow?



Applications of DEMs II

Flooding in New Orleans

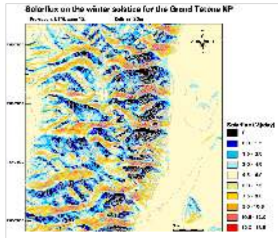
http://www.msnbc.msn.com/id/9130254/

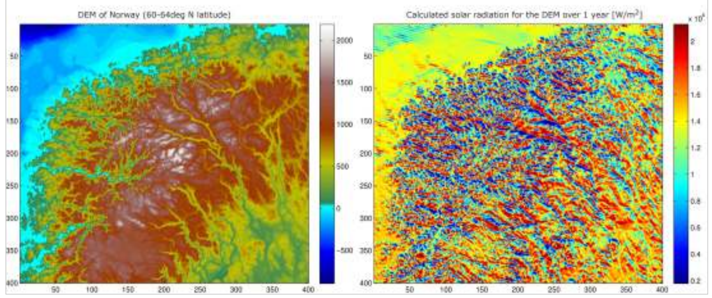


- Water mapping
  - where is the water
  - what is in the water?

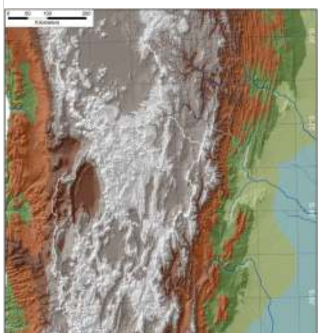
Applications of DEMs III

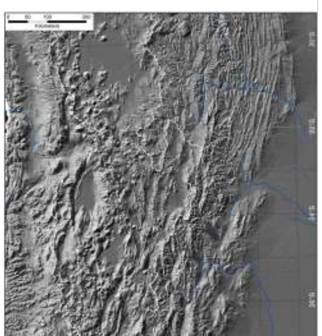
Applications of DEMs IV





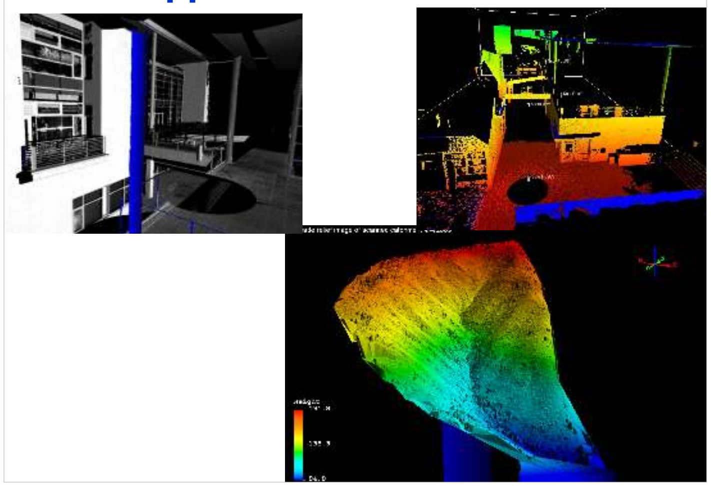
Applications of DEMs V



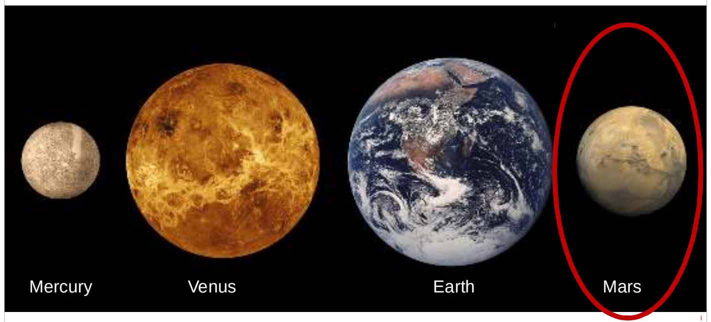


Applications of DEMs VI

Applications of DEMs VII



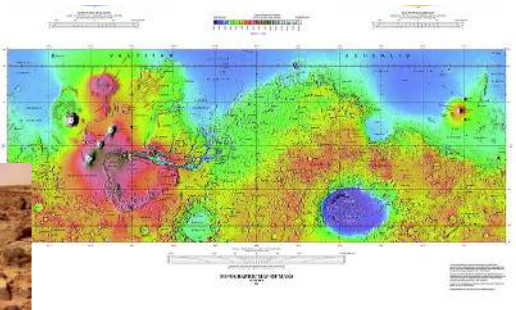
Earth-like planets



Sources: NASA

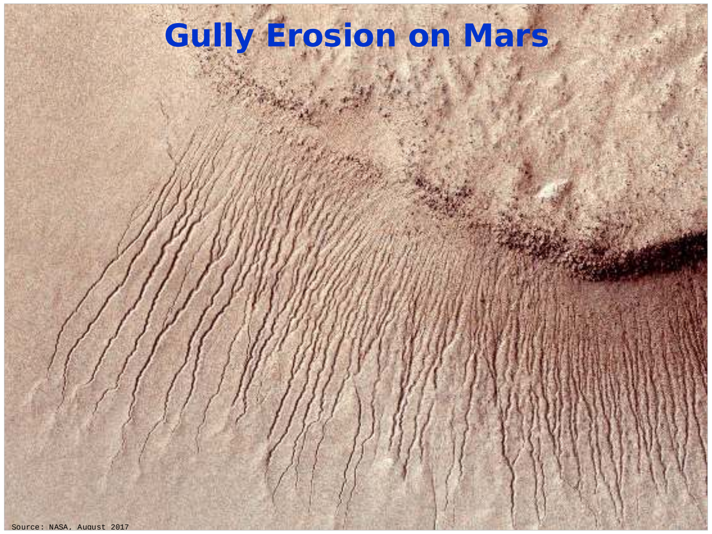
Applications of DEMs VIII

Topography and
Surface of Mars



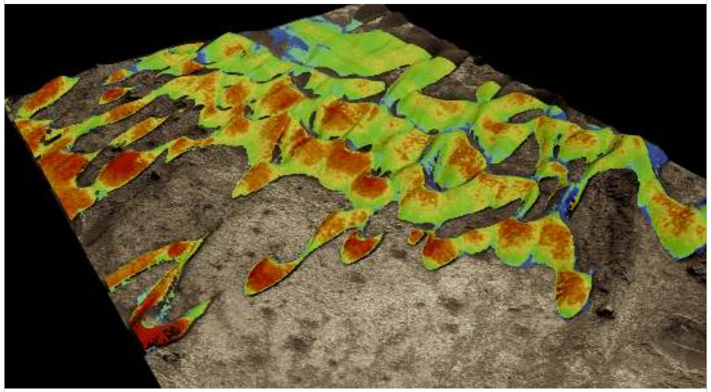
Mars: Shorelines and Tsunamis

Gully Erosion on Mars



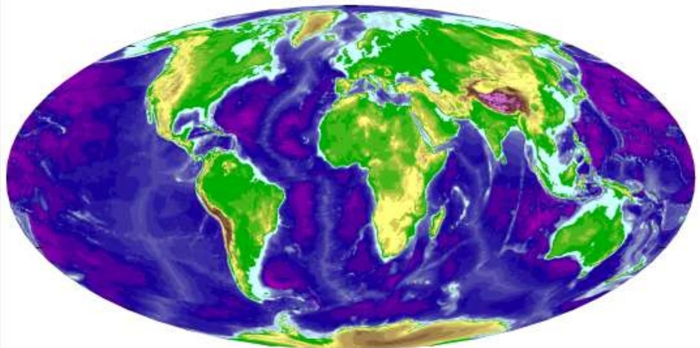
Source: NASA, August 2017

Mars: Dunes and Wind transport



Source: NASA, August 2017

Topography & Bathymetry

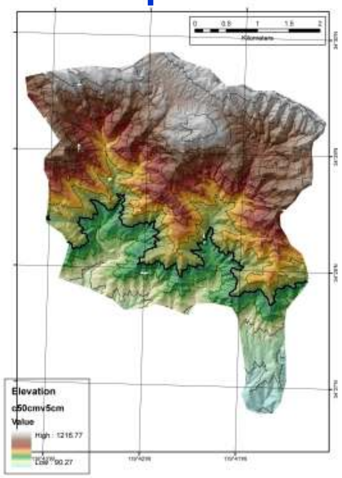


High-resolution DEM applications I

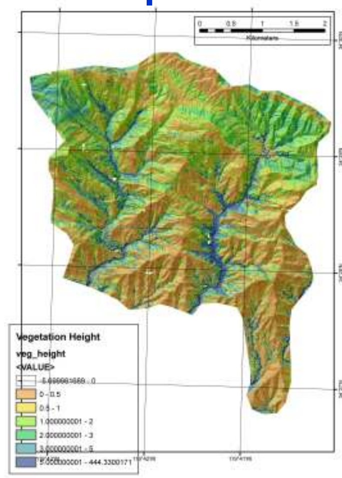
Panoramic view of the January 1, 2007, Northridge Bluff landslide. Bluff height in this view is about 140 m. View southeastward (USGS)

Lidar data collected after the January 2007 landslide. This image

LiDAR Example: Mission Cyn



LiDAR Example: Mission Cyn



Derived variables

- Primary use of DEMs is calculation of three main terrain variables:
  - **height**
    - altitude above datum
  - **aspect**
    - direction area of terrain is facing
  - **slope**

Calculating aspect

- Direction the land surface is facing measured in degrees or nominal classes (N, S, E, W, NE, SE, NW, SW, etc.)
  - use 3 x 3 filter and best fit tilted plane
  - determine aspect for target cell

10	9	8

Calculating slope I

- Slopes are calculated locally using a neighborhood function, based on a moving 3*3 window
- Distances are different in horizontal and vertical directions vs. diagonal

1.41…	1	1.41…
1	0	1
1.41…	1	1.41…

* cell size

- Hydrologic applications: only steepest slopes are used

Calculating slope II (30 m DEM)

340	335	330
337	332	330
330	328	320

(elevations)

8/42.47	3/30	-2/42.47
5/30	0	-2/30
-2/42.47	-4/30	-12/42.47

(difference/distance)

Calculating slope III (30 m DEM)

340	335	330
337	332	330
330	328	320

(elevations)

0.188	0.1	-0.047
0.166	0	-0.066

(slopes)

Calculating Slope

At every point in a DEM the slope can be defined as a function of gradients in the X and Y direction:

$$\text{Slope} = \arctan\sqrt{(fx)^2 + (fy)^2} \qquad (1)$$

$$S\left(x, y\right) = \frac{180^\circ}{\pi} \times \arctan\sqrt{\left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2},$$

The key in slope estimation is the computation of the perpendicular gradients fx and fy. Different algorithms, using different techniques to calculate fx and fy yield the diversity in

Calculating Slope

9	8	7
6	5	4
3	2	1

For example, slope, zi (i=1,2,…9) can be defined as:
1) Second-order finite difference 2FD (Fleming and Hoffer [3])
$fx=(z6-z4)/2g$ and $fy=(z8-z2)/2g$

Calculating Slope

9	$\boxed{8}$	7
$\boxed{6}$	5	$\boxed{4}$
3	$\boxed{2}$	1

For example, slope, zi (i=1,2,…9) can be defined as:
1) Second-order finite difference 2FD (Fleming and Hoffer [3])
$fx=(z6-z4)/2g$ and $fy=(z8-z2)/2g$

Smith, T., Rheinwalt, A., and Bookhagen, B.: Determining the optimal grid resolution for topographic analysis on an airborne lidar dataset, Earth Surf. Dynam., 7, 475–489, https://doi.org/10.5194/esurf-7-475-2019, 2019.

Calculating Slope

9	8	7
6	5	4
3	2	1

For example, slope, zi (i=1,2,…9) can be defined as:
Three-order Finite Difference Weighted by Reciprocal of Squared Distance 3FDWRSD (Horn [5])
$fx=(z3-z1+2\ (z6-z4)+z9-z7)/8g$

Calculating Slope

9	8	7
6	5	4
3	2	1

For example, slope, zi (i=1,2,…9) can be defined as:
Constrained Quadratic Surface Quadsurface (Wood [13])
$F(x,y)=ax2+by2+cxy+dx+ey+f$
$AX=Z=F(x,y)$

Calculating aspect

- Direction the land surface is facing measured in degrees or nominal classes (N, S, E, W, NE, SE, NW, SW, etc.)
  - use 3 x 3 filter and best-fit tilted plane
  - determine aspect for target cell

10	9	8
8	8	7
7	6	5

Calculating Slope and Aspect

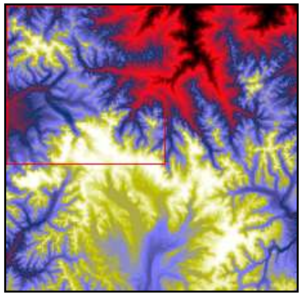
$$S\left(x,y\right) = \frac{180^\circ}{\pi} \times \arctan\sqrt{\left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2},$$

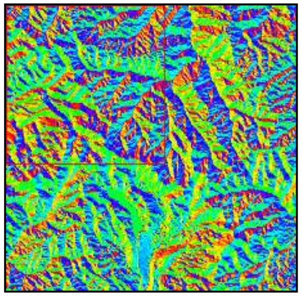
$$A\left(x,y\right) = \frac{180^\circ}{\pi} \times \arctan\left(\frac{\partial z}{\partial y} \times \frac{\partial x}{\partial z}\right) + 180^\circ,$$

Key in calculating slope and aspect is the calculation of the directional derivatives ∂z/∂x and ∂z/∂y.

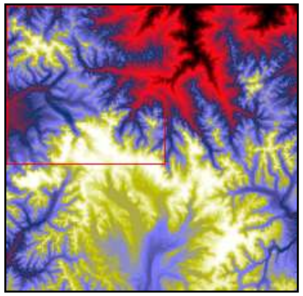
Smith, T., Rheinwalt, A., and Bookhagen, B.: Determining the optimal grid resolution for topographic analysis on an airborne lidar dataset, Earth Surf. Dynam., 7, 475–489, https://doi.org/10.5194/esurf-7-475-2019, 2019.

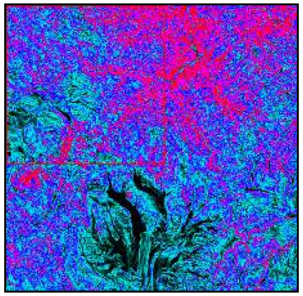
Examples Height and Aspect



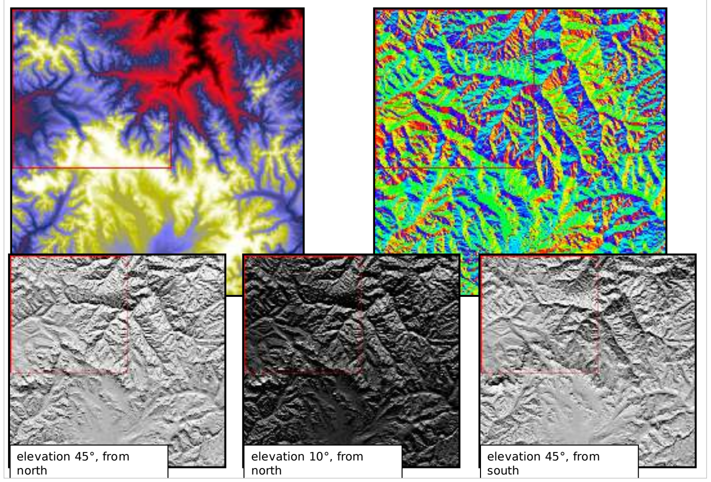


Examples Height and Slope





Examples Height and Hillshading



FlowDirection

340	335	330	340	345
337	332	325	335	340
330	328	320	330	335
328	326	310	320	328
320	318	305	312	315

FlowAccumulation

0	0	0	0	0
0	1	3	1	0
0	1	8	1	0

Various types of DEMs

DEMs can be generated from…

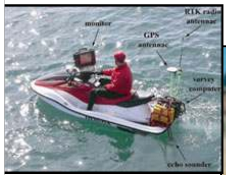
1. *Interpolation of survey points* (total station, GPS)
2. *Stereo Airphotos, Stereo Satellite Imagery* (Stereogrammetry, Photogrammetry)
3. *Digitizing topographic maps* (contour lines)
4. *Radar interferometric images* (SRTM – Shuttle Radar Topographic Mission)

GPS – Global Positioning System

- GPS: active sensor in the L band [1.57542 GHz (L1 signal) and 1.2276 GHz (L2 signal)]
- GPS has one purpose: **to determine the geographic x,y,z and time of a GPS detector**. Every point on the planet has a unique geographic location, and can be measured at a specific time.

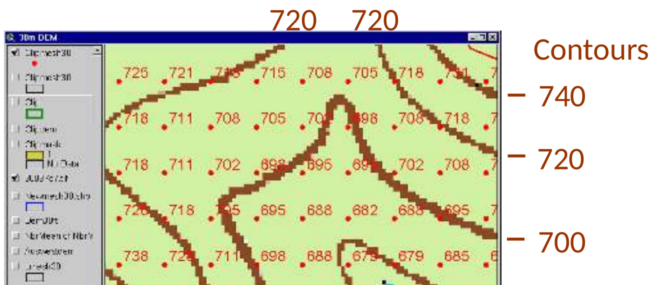
Band Designations (common wavelengths shown in parentheses)	*Wavelength (λ) in cm*	*Frequency (ν) in GHz*
K	1.18 - 1.67	26.5 to 18.0
K_a (0.86 cm)	0.75 - 1.18	40.0 to 26.5
K_u	1.67 - 2.4	18.0 to 12.5
X (3.0 and 3.2 cm)	2.4 - 3.8	12.5 - 8.0
C (7.5, 6.0 cm)	3.8 - 7.5	8.0 - 4.0
S (8.0, 9.6, 12.6 cm)	7.5 - 15.0	4.0 - 2.0
L (23.5, 24.0, 25.0 cm)	15.0 - 30.0	2.0 - 1.0
P (68.0 cm)	30.0 - 100	1.0 - 0.3

GPS – collecting data with a Differential GPS



Sources: USGS

GPS – points to contour lines or DEMs

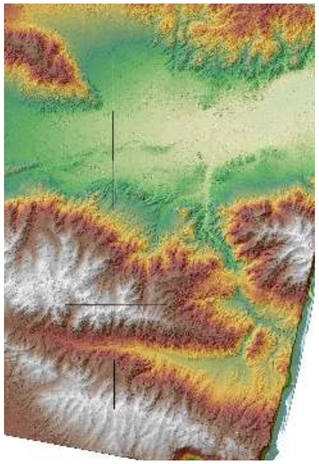


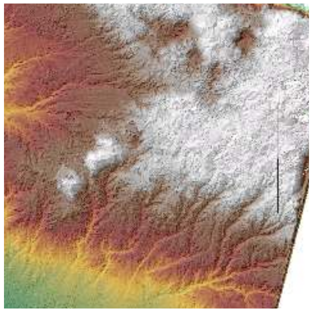
Various types of DEMs

DEMs can be generated from…

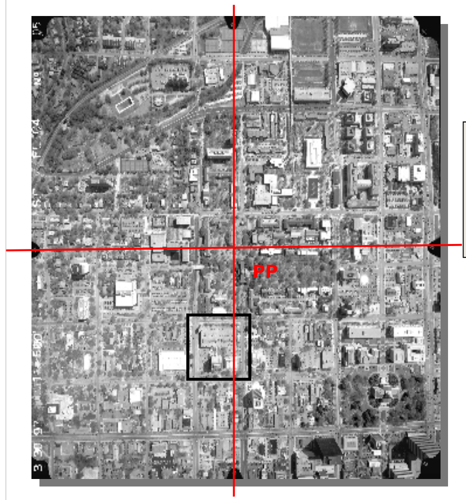
1. *Interpolation of survey points* (total station, GPS)
2. *Stereo Airphotos, Stereo Satellite Imagery* (Stereogrammetry, Photogrammetry)
3. *Digitizing topographic maps* (contour lines)
4. *Radar interferometric images* (SRTM – Shuttle Radar Topographic Mission)

Example: Stereogrammetry – ASTER





Artifacts! (aka DEM errors) for a 15m DEM

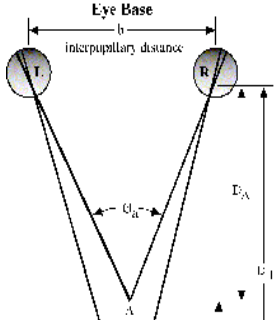


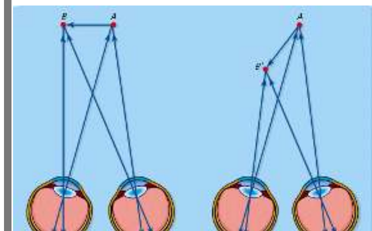
Flightline #4
Photo #5

Columbia, SC
Original scale = 1:6,000
Focal length = 6" (152.82 mm)
March 30, 1993

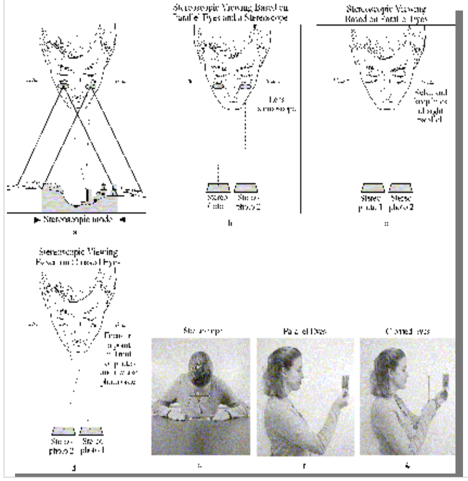
Measurement of Object Height From A Single Aerial Photograph Based on Relief Displacement

Parallactic Angles used During Depth Perception

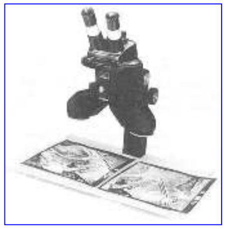




Stereoscopy I



Stereoscopy II

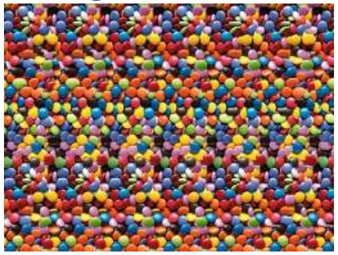


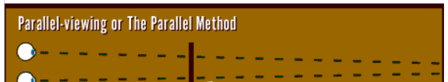
Zoom stereoscope

Mirror stereoscope

Scanning mirror stereoscope

Hidden 3D Images





Stereoscopy III

Stereoplotters - precision instruments designed to duplicate the exact relative position and orientation of the aerial camera at the time of photo acquisition to recreate the stereo model. Relief displacement is removed creating a ***planimetric map***.

Soft-copy photogrammetry workstations (aka computers with ENVI)- computer software recreates the stereo model and allows for digital mapping

Collinearity equations I

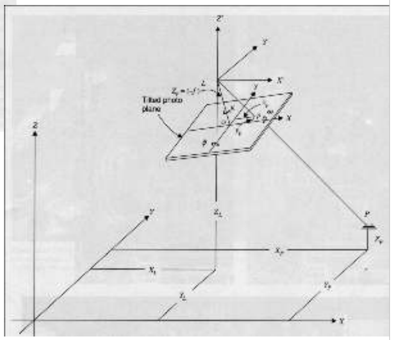
$$x_p = -f\left[\frac{m_{11}(X_P - X_L) + m_{12}(Y_P - Y_L) + m_{13}(Z_P - Z_L)}{m_{31}(X_P - X_L) + m_{32}(Y_P - Y_L) + m_{33}(Z_P - Z_L)}\right]$$

$$y_p = -f\left[\frac{m_{21}(X_P - X_L) + m_{22}(Y_P - Y_L) + m_{23}(Z_P - Z_L)}{m_{31}(X_P - X_L) + m_{32}(Y_P - Y_L) + m_{33}(Z_P - Z_L)}\right]$$

where

x_p, y_p = image coordinates of any point p
f = focal length
X_P, Y_P, Z_P = ground coordinates of point P
X_L, Y_L, Z_L = ground coordinates of exposure station L

$m_{11}, \ldots, m_{33}$ = coefficients of a 3x3 rotation matrix, defined by the angles ω, ϕ, κ that transforms the ground coordinate system to the image coordinate system



Collinearity indicates that a set of points are on a single straight line: the equation describe the relationships among image coordinates, ground coordinates, the exposure station position, and angular orientation of the image/photograph.

Collinearity equations II

$$x_p = -f\left[\frac{m_{11}(X_P - X_L) + m_{12}(Y_P - Y_L) + m_{13}(Z_P - Z_L)}{m_{31}(X_P - X_L) + m_{32}(Y_P - Y_L) + m_{33}(Z_P - Z_L)}\right]$$

$$y_p = -f\left[\frac{m_{21}(X_P - X_L) + m_{22}(Y_P - Y_L) + m_{23}(Z_P - Z_L)}{m_{31}(X_P - X_L) + m_{32}(Y_P - Y_L) + m_{33}(Z_P - Z_L)}\right]$$

where

x_p, y_p = image coordinates of any point p
f = focal length
X_P, Y_P, Z_P = ground coordinates of point P
X_L, Y_L, Z_L = ground coordinates of exposure station L

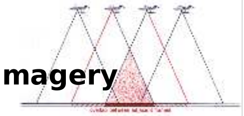
$m_{11}, \ldots, m_{33}$ = coefficients of a 3x3 rotation matrix, defined by the angles ω, ϕ, κ that transforms the ground coordinate system to the image coordinate system

If the location of the exposure station is known (X_L, Y_L, Z_L), as well as the rotation angles ω, ϕ, κ (-> calculate m_{xx}), then any position on the ground (X_P, Y_P, Z_P) can be located on the photo.

X_L, Y_L, Z_L and ω, ϕ, κ are the exterior orientation of a photograph/image and can be constrained by selecting GCPs.

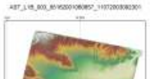
Orthorectification:
If you know the ground coordinates of point P (X_P, Y_P, Z_P - e.g, through a DEM), and you know X_L, Y_L, Z_L and ω, ϕ, κ (exterior orientation through GCPs), than you can correct for x_p and y_p, the image coordinates.
DEM creation:
If you know x_p and y_p (image coordinates), and X_L, Y_L, Z_L and ω, ϕ, κ (exterior orientation through GCPs), and you have two views of

Stereogrammetry



Stereo Airphotos / Satellite Imagery

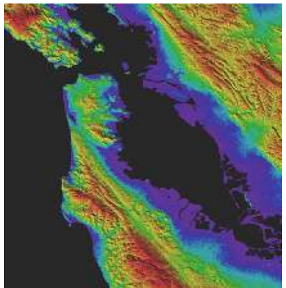
- DEM can be created for overlapping area (60% for airphotos, 85% for ASTER)



ASTER GDEM

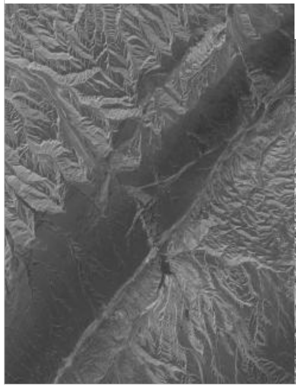
August 2019: Version 3 of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) is now available from NASA's Land Processes Distributed Active Archive Center (LP DAAC).

The ASTER GDEM covers land surfaces between 83°N and

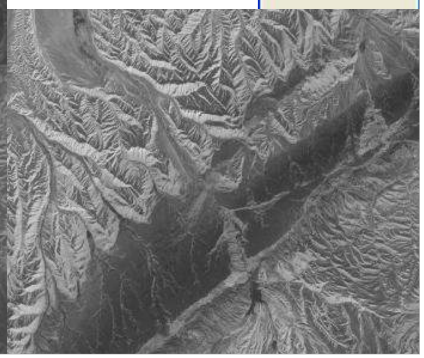


Stereogrammetry

Viewing angle: 26.8°



Viewing angle: -20.1°

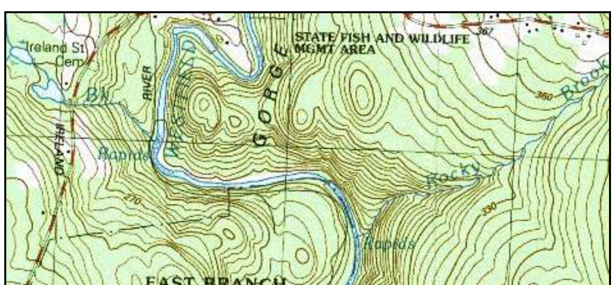


Various types of DEMs

DEMs can be generated from…

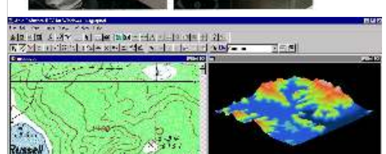
1. *Interpolation of survey points* (total station, GPS)
2. *Stereo Airphotos, Stereo Satellite Imagery* (Stereogrammetry, Photogrammetry)
3. *Digitizing topographic maps* (contour lines)
4. *Radar interferometric images* (SRTM – Shuttle Radar Topographic Mission)
5. *LiDAR* – LIght Detection And Ranging

Digitizing Contour Lines I



Digitizing Contour Lines II

Penn State Univ



Various types of DEMs

DEMs can be generated from…

1. *Interpolation of survey points* (total station, GPS)
2. *Stereo Airphotos, Stereo Satellite Imagery* (Stereogrammetry, Photogrammetry)
3. *Digitizing topographic maps* (contour lines)
4. *Radar interferometric images* (SRTM – Shuttle Radar Topographic Mission)
5. *LiDAR* – LIght Detection And Ranging

Useful Text

http://www2.geog.ucl.ac.uk/~mdisney/teaching/PPRS/PPRS_7/

esa_sar_tutorial.pdf

A Tutorial on Synthetic Aperture Radar

©DLR

ALBERTO MOREIRA, PAU PRATS-IRAOLA, MARWAN YOUNIS, GERHARD KRIEGER, IRENA HAJNSEK, AND KONSTANTINOS P. PAPATHANASSIOU
Microwaves and Radar Institute of the German Aerospace Center (DLR), Germany

Abstract—Synthetic Aperture Radar (SAR) has been widely used for Earth remote sensing for more than 30 years. It provides high-resolution, day-and-night and weather-independent images for a multitude of applications ranging from geoscience and climate change research, environmental and Earth system monitoring, 2-D and 3-D mapping, change detection, 4-D mapping (space and time), security-related applications up to planetary exploration. With the advances in radar technology and geo/bio-physical parameter inversion modeling in the 90s, using data from several airborne and spaceborne systems, a paradigm shift occurred from the development driven by the technology push to the user demand pull. Today, more than 15 spaceborne SAR systems are being operated for innumerous applications. This paper provides first a tutorial about the SAR principles and theory, followed by an overview of established techniques like polarimetry, interferometry and differential interferometry as well as of emerging techniques (e.g., polarimetric SAR interferometry, tomography and holographic tomography). Several application examples including the associated parameter inversion modeling are provided for each case. The paper also describes innovative technologies and concepts like digital beamforming, Multiple-Input Multiple-Output (MIMO) and bi- and multi-static configurations which are suitable means to fulfill the increasing user requirements. The paper concludes with a vision for SAR remote sensing.

Digital Object Identifier 10.1109/MGRS.2013.2248301
Date of publication: 17 April 2013

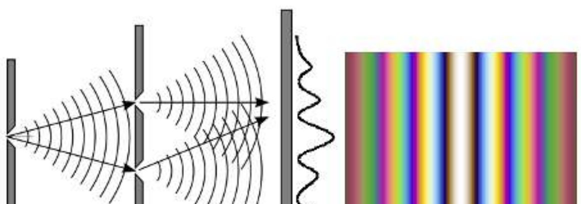
I. INTRODUCTION

Synthetic Aperture Radar (SAR) has entered into a golden age. More than 15 spaceborne SAR sensors are being operated today and 10 new SAR systems will be launched within the next 5 years. SAR is unique in its imaging capability: It provides high-resolution two-dimensional images independent from daylight, cloud

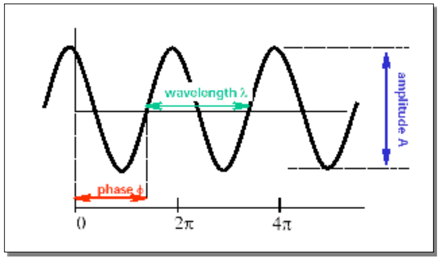
6 2168-6831/13/$31.00©2013IEEE IEEE GEOSCIENCE AND REMOTE SENSING MAGAZINE MARCH 2013

Interferometry

Interferometry is the study of interference patterns created by combining two sets of radar signals (analogy: water with a film of oil on it - light rays bouncing off the smooth surfaces of the oil and underlying water, making interference patterns)

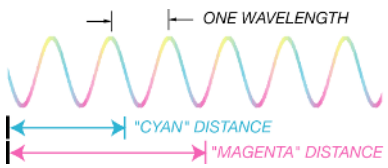


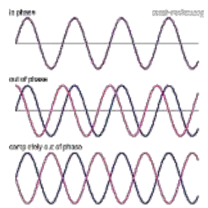
RADAR Fernerkundung



- Amplitude depends on target properties (structure and dielectric properties)

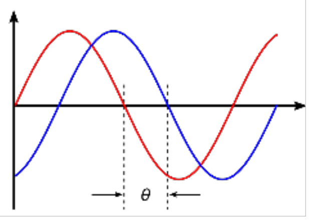
Phase of a wave





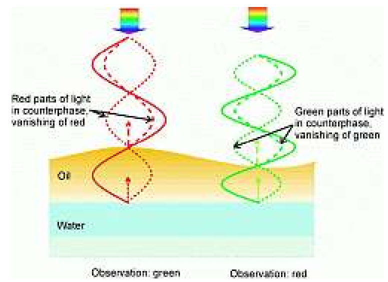
Distance traveled is measured as phase of wave

Phase difference
(or Phase shift):



Interferometry

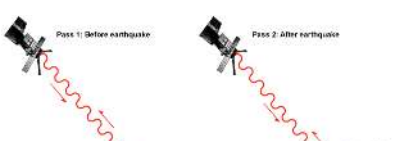
On the left side, the incident white light is reflected from the top and bottom side of the oil film. The thickness of the oil film is such that after superposition of the reflected light the red components are extinguished. Consequently this area appears in the light of the complementary color, i.e. green.
On the right side area the oil film is thinner, so extinction is just complied with for a shorter, e.g. green light wavelength, so that this area appears in red light.

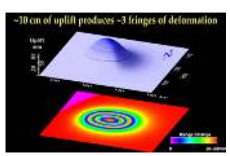


Source: Wikipedia

Interferometry (InSAR)

Interferometry is the study of interference patterns created by combining two sets of radar signals (analogy: water with a film of oil on it - light rays bouncing off the smooth surfaces of the oil and underlying water, making interference patterns)

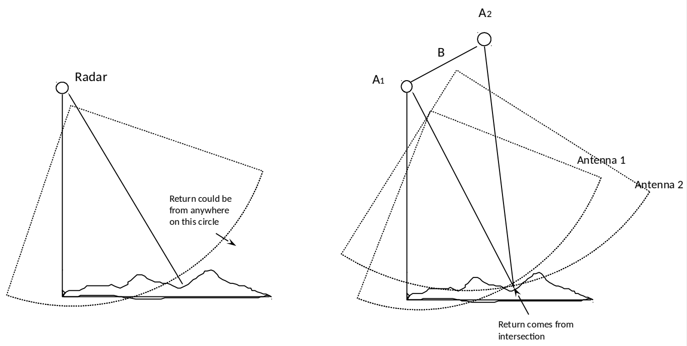




Interferometry

- Interferometry: The use of interference phenomena for purposes of precise distance measurements
- Uses two or more SAR radar images to generate spatial patterns (maps) of surface deformation or digital elevation by using the phase differences of the waves returning to the instrument.

SAR interferometry



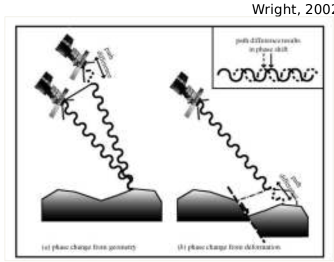
Single antenna SAR

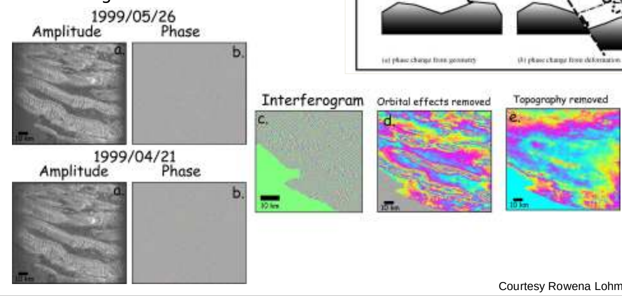
Interferometric SAR

SAR interferometry

Wright, 2002

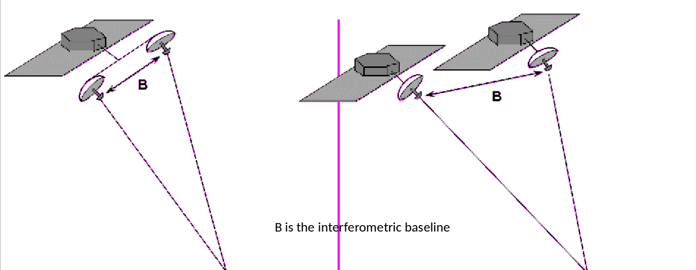
- Two Radar images from space: Data is complex: has amplitude and phase
- Phase change between images depends on several factors that must be removed before measuring deformation





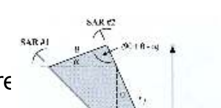
Courtesy Rowena Lohman

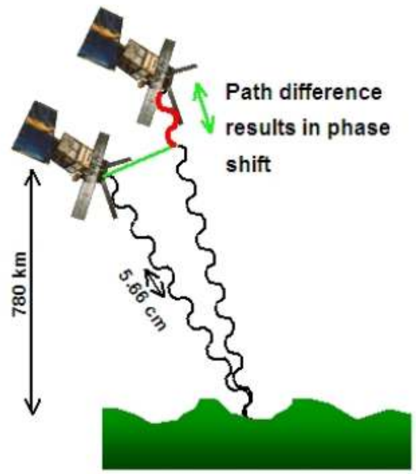
SAR interferometry



Interferometry - InSAR

- Type of SAR using multiple images to capture 3-D structure and elevation
- Images acquired 1) from different locations <u>or</u> 2) at different times
- Multiple pass vs. single pass: two Radars, spaced apart vs. same Radar, on different orbits
- Dual Radar acquisitions capture how out of phase two signals are

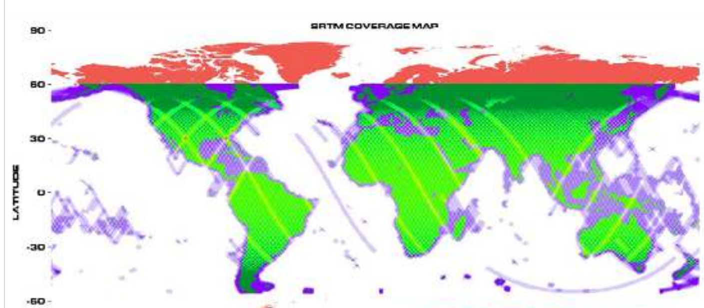




Single-pass interferometry

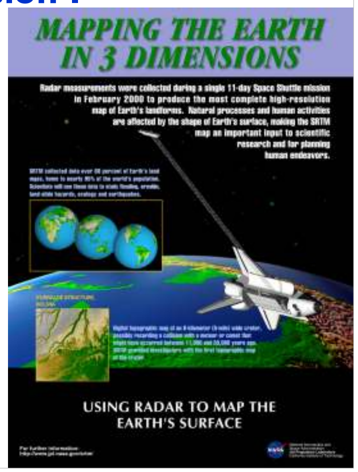
Single-pass interferometry. Two antennas offset by known baseline.

SRTM coverage map

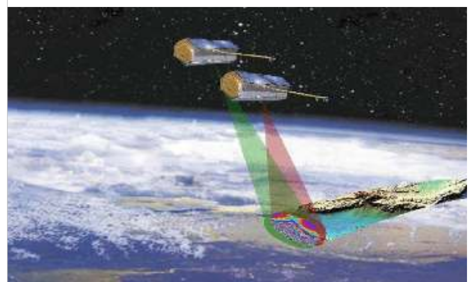


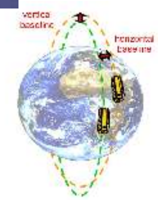
SRTM – Shuttle Radar Topographic Mission I

- SRTM mapped nearly all of Earth’s landmass between latitudes 60 degrees north and 56 degrees south. That is about 120 million square kilometers (46 million square miles).
- More than 12 terabytes of radar data were acquired for production of the elevation model plus a radar image “snapshot” of Earth.
- The full-resolution SRTM digital elevation model shows detail as small as about 30 meters (98 feet), about the size of a basketball court.
- The SRTM elevation model is the first high-resolution, near-global topographic map of Earth.

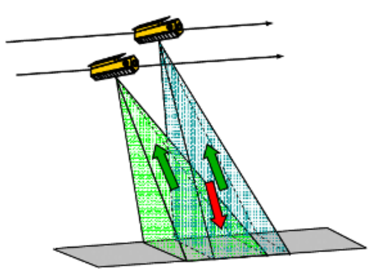


TerraSAR-X / TanDEM-X





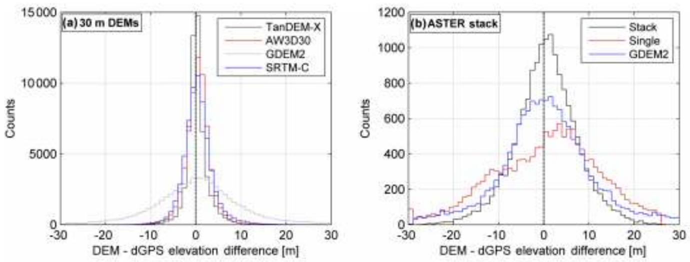
TerraSAR-X / TanDEM-X



Validation of digital elevation models (DEMs) and comparison of geomorphic metrics on the southern Central Andean Plateau

Dataset (short name)	Data type	Resolution (m)	Source	Notes
SRTM C-band (SRTM-C)	Radar, edited global product	30	Public, https://lta.cr.usgs.gov/SRTM1Arc	Collected in February 2000, released 2014 (previously only US coverage).
ASTER GDEM Version 2 (ASTER GDEM2)	Optical, edited global product	30	Public, https://asterweb.jpl.nasa.gov/gdem.asp	Released 2011, update of ASTER GDEM1 released 2009. Generated by automated processing and stacking of ASTER L1A stereopairs by NASA and METI.
ASTER L1A stereo-pair stack (ASTER stack)	Optical, raw stereopairs	30	Public, http://reverb.echo.nasa.gov/reverb/	Stacked DEM generated for this study by stereogrammetric processing of eight raw L1A stereopairs (Sect. 3.2 ASTER stacking).
ALOS World 3D (AW3D5 and AW3D30)	Optical, edited global product	5/30	Public (30 m), http://www.eorc.jaxa.jp/ALOS/en/aw3d30/ Commercial (5 m), http://aw3d.jp/en/	5 m DEM released 2015 as highest resolution commercial global DEM, with down sampled 30 m research version released 2016.
Single-CoSSC TerraSAR-X/ TanDEM-X	Radar, raw interferograms	10	Research agreement, http://sss.terrasar-x.dlr.de/	DEMs generated for this study by single CoSSC TerraSAR-X/TanDEM-X radar pairs. Same data used by DLR [illegible]

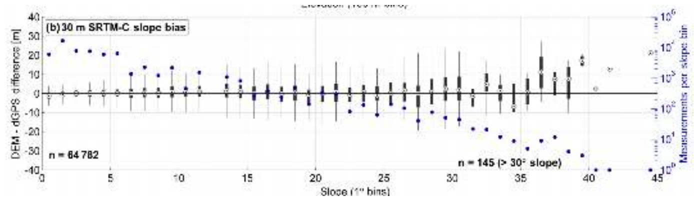
Comparing DEMs: Validation



Vertical uncertainties for (a) global 30 m DEMs and (b) ASTER 30 m DEMs. Plots have been normalized by mean offsets.
Note the order of magnitude difference in counts, as panel (b) covers only the Pocitos Basin (~ 2500 km2), whereas panel (a) spans all dGPS measurements (~ 50 000 km2) stretching over a 4000 m elevation range.

Purinton, B. and Bookhagen, B. (2017)

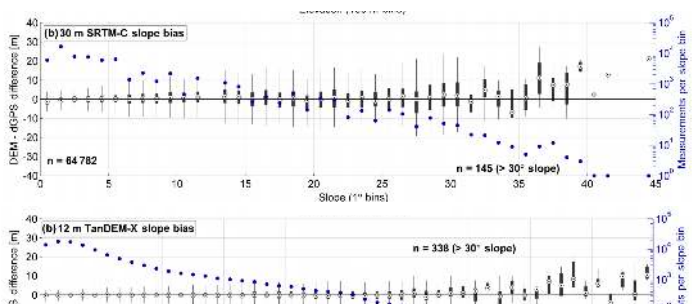
Comparing DEMs: Validation

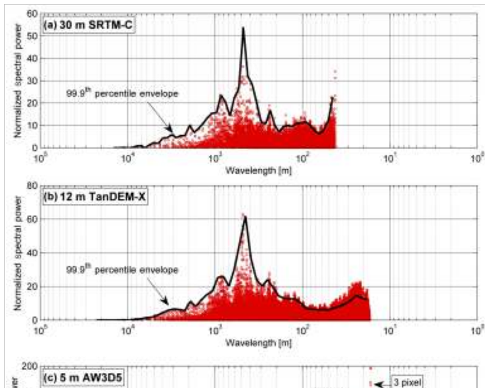


Slope (eight-connected neighborhood calculated) vertical uncertainties from 30 m SRTM-C.
Median elevation difference (black circles) with 25–75th percentile range (boxes) and first and 99th percentile outlier cutoff (whiskers) plotted for each bin on left axis.
Number of measurements indicated (n) with measurements per bin plotted as colored circles on right axis.

Purinton, B. and Bookhagen, B. (2017)

Comparing DEMs: Validation





One-dimensional normalized power spectra for (a) 30 m SRTM-C, (b) 12 m TanDEM-X, and (c) 5 m AW3D5 plotted against wavelength (frequency−1). Wavelength here is equivalent to spatial resolution in pixels.
Note the spikes in the AW3D5 data. These spikes correspond to 2–8 pixel (10–40 m wavelength) steps in this 5 m DEM.