EUFAR - EUropean Facility for Airborne Research

Education & Training

LIDAR
measurement principle and georeferencing

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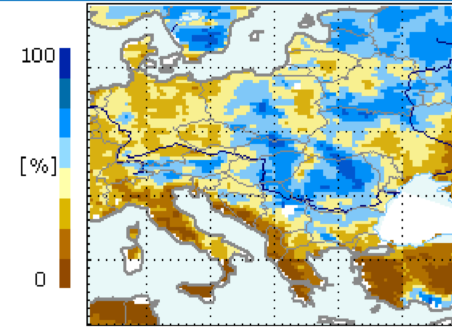
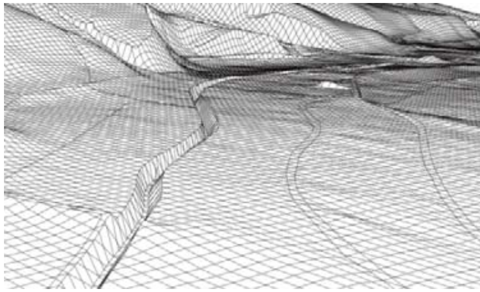
ADDRESSS training course, 19-28 August 2010, Balaton Limnological Research Institute , Hungary

Institute of Photogrammetry and Remote Sensing – I.P.F.

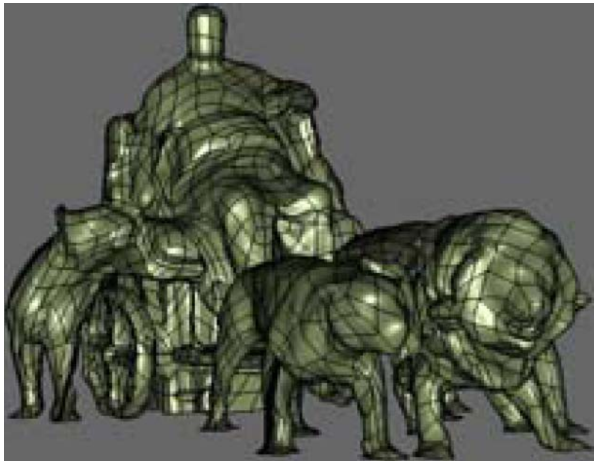
Christian Doppler Forschungsgesellschaft



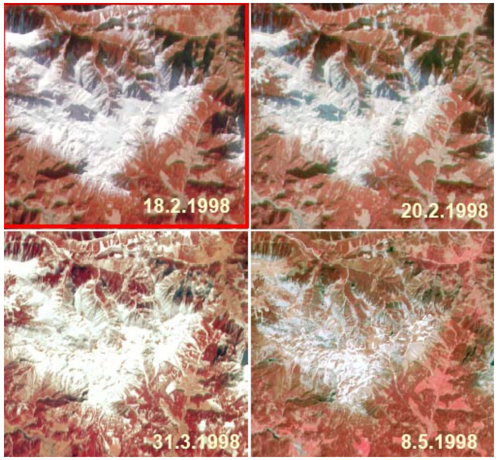
- Prof. W. Wagner (Head), Professor in Remote Sensing
  - Radar Remote Sensing
  - Physical aspects of Laser Scanning
- Prof. N. Pfeifer, Professor in Photogrammetry
  - Photogrammetry
  - Geometrical aspects of Laser Scanning



- Assoc. Prof. J. Jansa
  - Optical Remote Sensing
  - Digital Image Processing



- Staff: ~40
  (incl. ~10 faculty staff)
  - Geodesists, geographers, environmental engineers, physicists, computer scientists



- Christian Doppler Laboratory
  "Spatial Data from Laser Scanning and Remote Sensing"

Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology

→ http://archpro.lbg.ac.at/

Content

- Part I - LIDAR principle
  - LIDAR principle
  - Laser Scanning - Laser beam deflection
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- Part II - Principle of Georeferencing
  - Direct Georeferencing
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- Part III
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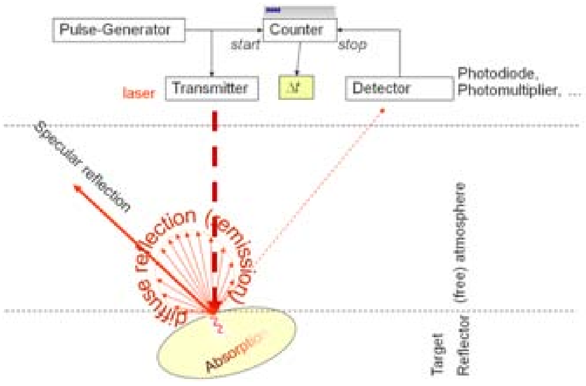
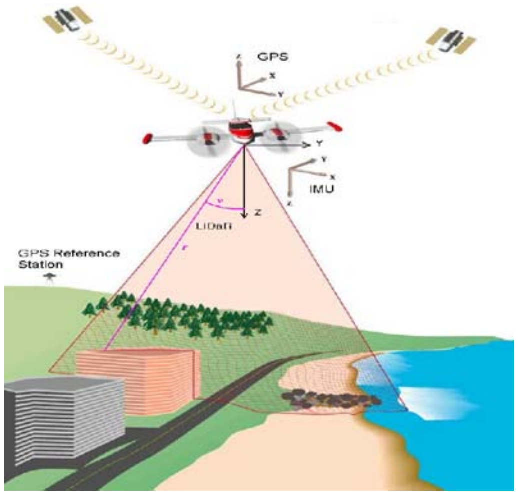
  - Surface and Terrain Models





Terms

- LASER = Light Amplification by Stimulated Emission of Radiation
- LIDAR = Light Detection and Ranging

  (LADAR = Laser Detection and Ranging)
- Static Laser Ranging = static LIDAR
- Kinematic Laser Ranging = Laser Profiling = along track LIDAR
- Static Laser Scanning (LS) / Scanning LIDAR
- Kinematic Laser Scanning (LS) / Scanning LIDAR = along and across track LIDAR
- LS on different platforms
  - Static mode
    - Terrestrial Laser Scanning (TLS)
  - Kinematic mode
    - Airborne Laser Scanning (ALS)
    - Satellite Laser Ranging (SLR)

Physical principles, motivation

- LRF: Laser Range Finding
  - Active distance measurement: sensor-object-sensor
  - Possible for „none cooperative targets“, resp. reflectorless rangeing (without prisms)
  - Laser technology is highly developed, therefore there exists the possibility to select an approbiate wavelength
  - Pairing of wavelength and detector (green/red-nIR)
  - Strongly focused beam (comp. radar)
- In more general Terms
  - Study of an object by emitting a certain amount of laser energy and by the analysis of the backscattered energy (range, amplitude, etc.)

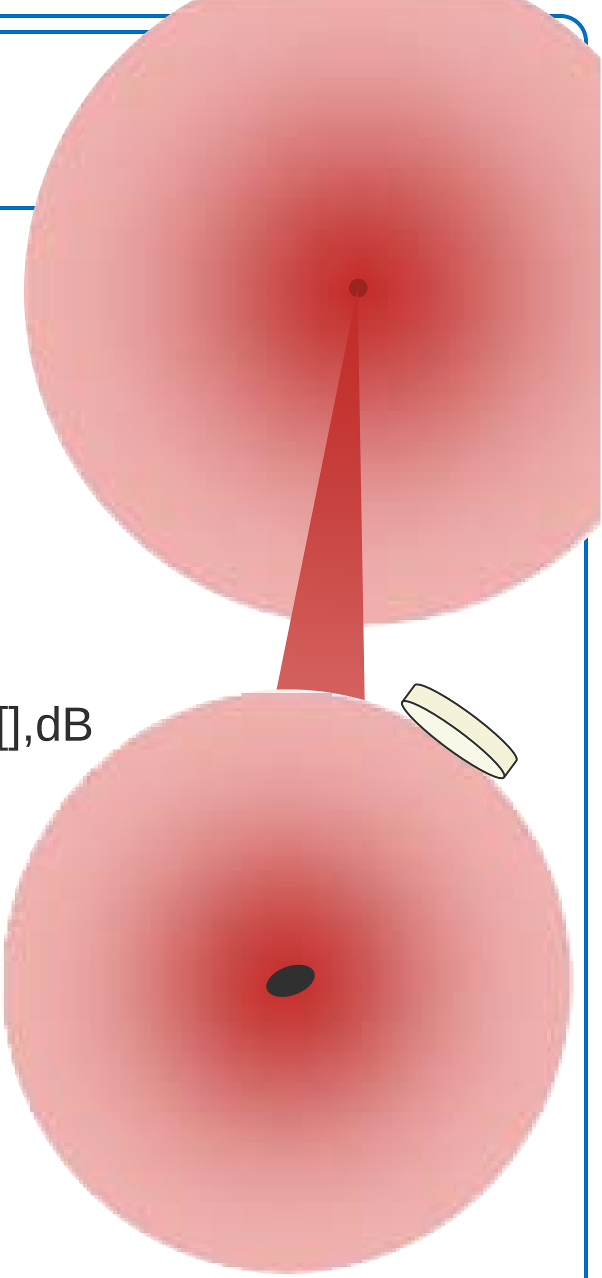
Resolution limits

- … „strongly focused beam "
- Physical limit defined by the effect of diffraction
- $\gamma = k*\lambda/D$
  - γ = beam divergence
  - λ = wavelength
  - D = aperture diameter
  - k = factor that describes the illumination of the aperature (~1 bis 2,44)
- Laser resolution in the optical range (camera, laser) and therefore better than in radar
- Dimensions
  aperture of digital aerial cameras : cm
  aperture of a LIDAR instrument : mm
- Radar: increase in resolution by a synthetic aperture (SAR)
  (In principle also for LIDAR possible)

Laser equation I

$$P_R = \frac{P_T}{4\pi R^2} \times \frac{4\pi}{\theta_T^2} \times \frac{\sigma}{4\pi R^2} \times \frac{\pi D^2}{4} \times \eta_{\mathrm{ATM}} \eta_{\mathrm{SYS}} + P_{\mathrm{BK}}$$

- Received power P_R [W]
- Transmitted power P_T [W]
- Equally distributed along a sphere [m^{-2}]
- Antenna gain G_T (opening angle in respect to the sphere) [],dB
- Backscatter cross section of the target σ [m^2]
- Equally distibuted backscatter along a sphere [m^{-2}]
- Receiver aperature D [m^2]
- Atmospheric and system loss η_{ATM}, η_{SYS} []
- Background radiation (sun, shot noise, …) P_{BK} [W]



Laser equation II

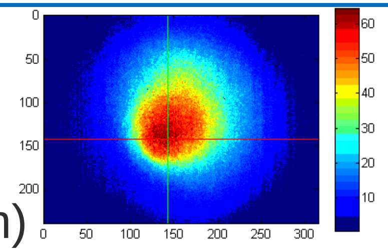
$$P_R = \frac{P_T}{4\pi R^2} \times \frac{4\pi}{\theta_T^2} \times \frac{\sigma}{4\pi R^2} \times \frac{\pi D^2}{4} \times \eta_{\mathrm{ATM}} \eta_{\mathrm{SYS}} + P_{\mathrm{BK}}$$

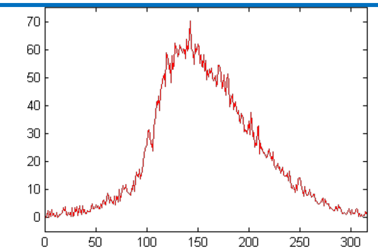
Missing factors

- Temporal distribution of the energy within the puls (along the beam)
- Lateral energy distribution
- Backscatter cross section
    - Size, resp. Prolongation across the beam
    - Backscatter characteristic in respect to direction and power
    - Prolongation along the beam

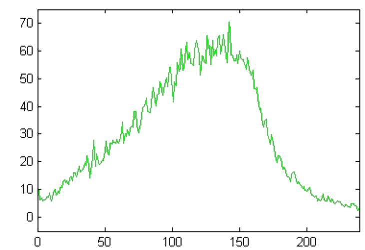
Laser beam

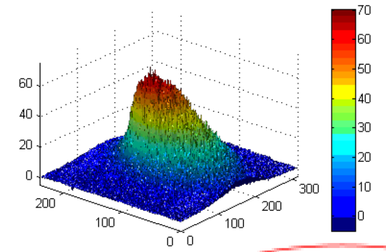
- Energy distribution across
  Approximately Gaussian
  (Jutzi et al., 2003, wavelength 1543nm)



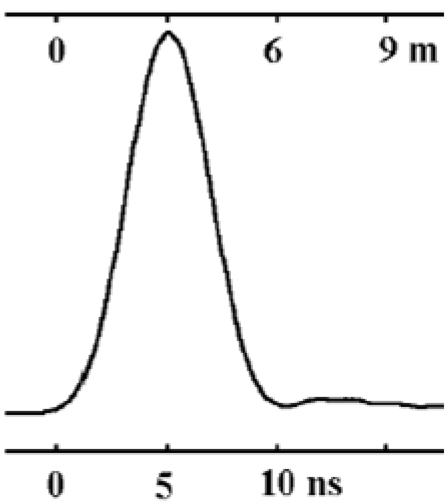


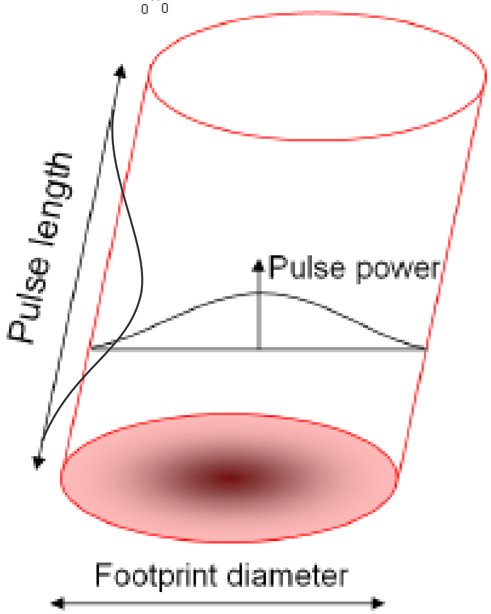
- Energy distribution along
  Approximately Gaussian
  „Riegl“-Puls, wavelength 1.5µm
  (Wagner et al., 2004)





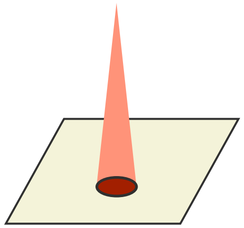
- Beam divergence
  Diffraction, $\gamma = \lambda / D$





Backscatter cross section I

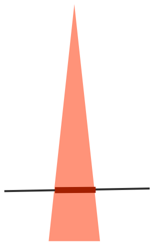
$$P_R = \frac{P_T}{4\pi R^2} \times \frac{4\pi}{\theta_T^2} \times \frac{\sigma}{4\pi R^2} \times \frac{\pi D^2}{4} \times \eta_{\mathrm{ATM}} \eta_{\mathrm{SYS}} + P_{\mathrm{BK}}$$



- Size of the target
  - Extended target

    $A=R^2\theta_T^2\pi/4$ $\quad P_R \propto R^2$

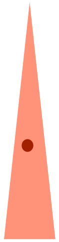
    Example: open terrain



  - Linear Target

    $A=R\theta_T d$ $\quad P_R \propto R^3$

    Example: wire



  - Point (very small) Target

    $A=\mathrm{const}$ $\quad P_R \propto R^4$

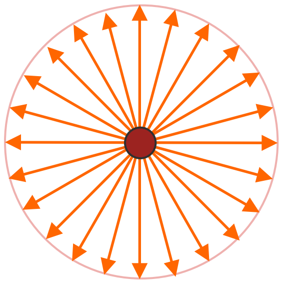
    Example: leaf

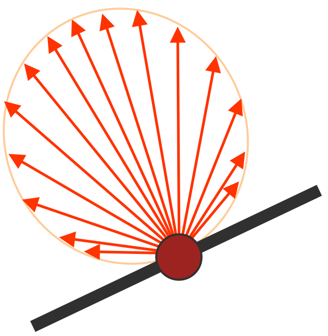
Backscatter cross section II

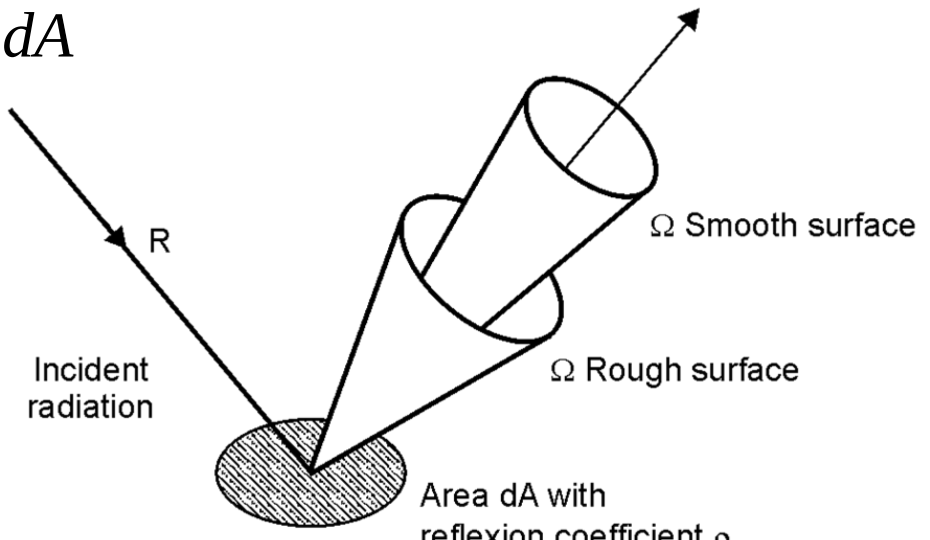
$$P_R = \frac{P_T}{4\pi R^2} \times \frac{4\pi}{\theta_T^2} \times \frac{\sigma}{4\pi R^2} \times \frac{\pi D^2}{4} \times \eta_{\mathrm{ATM}} \eta_{\mathrm{SYS}} + P_{\mathrm{BK}}$$

- Backscatter
  - Isotrop $\sigma = \rho A$
  - Lambert'sch $\sigma = 4\rho A$ (orthogonal incidence)
  - General:

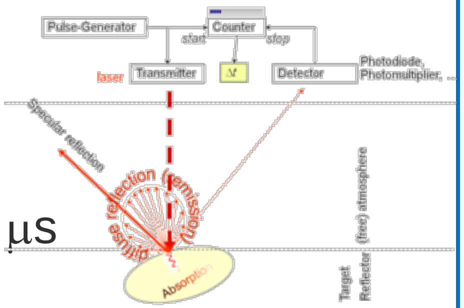
$$\sigma = \frac{4\pi}{\Omega} \cdot \rho \cdot dA$$



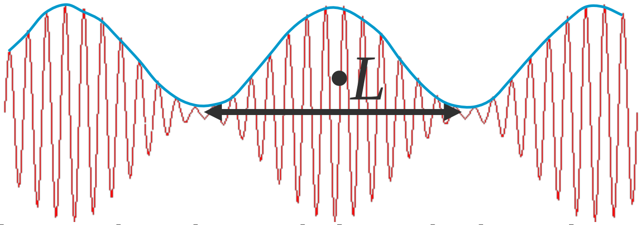




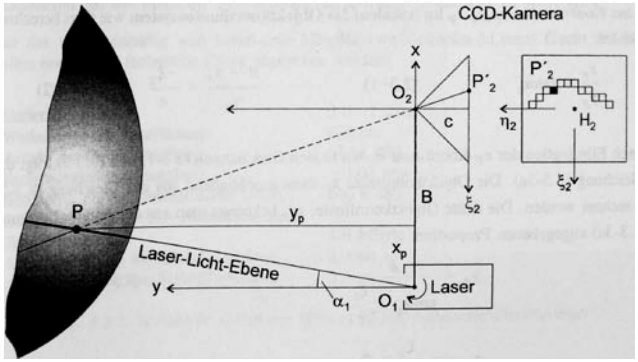
Ranging Principles using Lasers



- Pulse run time
  - measure time between sent and received pulse
  - 1cm = 0.03 ns (nano-seconds = 0.00000000003 seconds)
  - round trip time for 1000m between scanner and object = 6 μs
  - suitable for longer ranges (using higher pulse energies)
- Phase shift



  - modulate laser light with harmonic signal (image: amplitude modulation)
  - measure phase difference between emitted and received modulated signal
- Triangulation

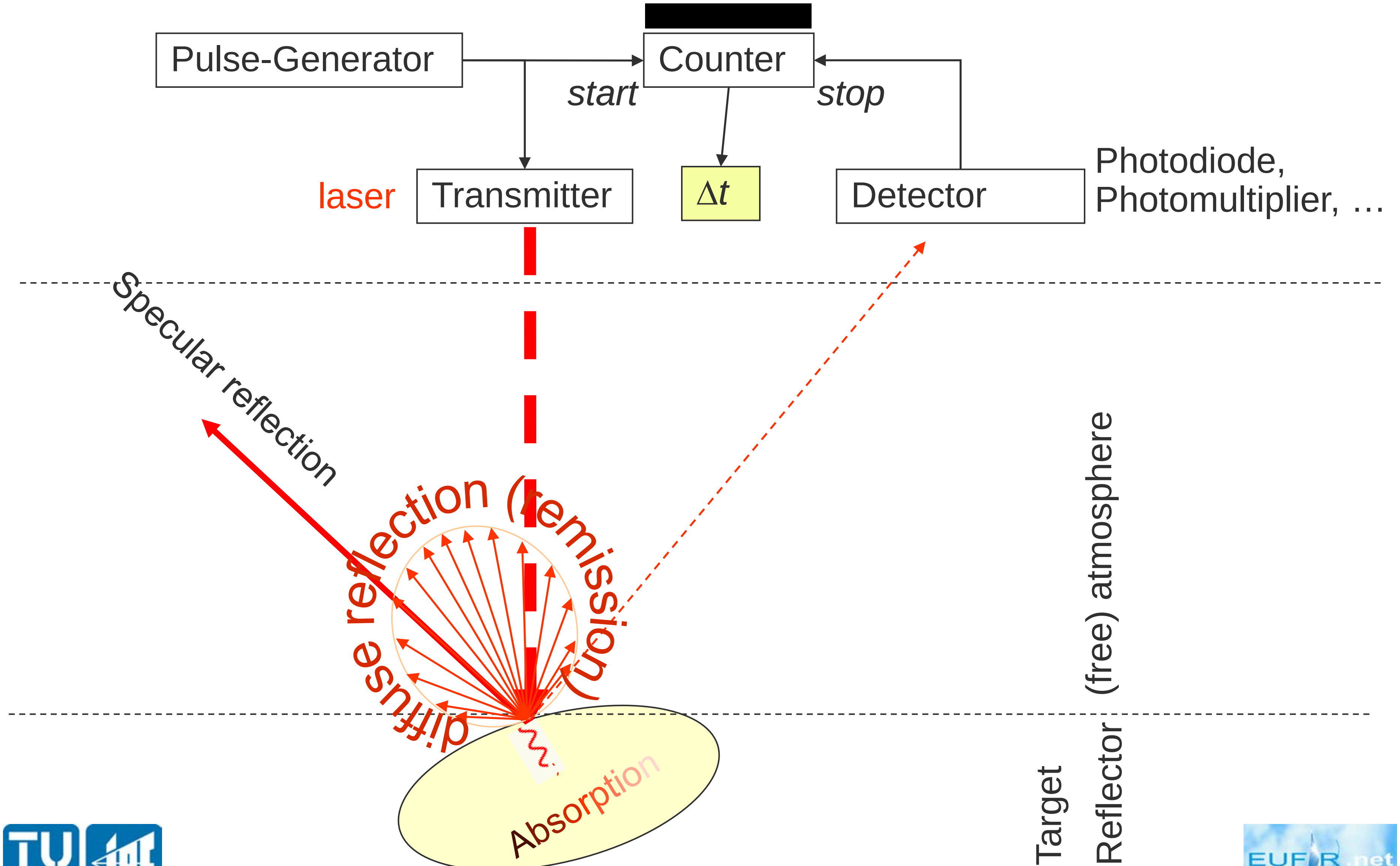


  - plane of (laser) light sweeps over object: angle $\alpha = \alpha(t)$
  - light plane — object: intersection mapped in digital image
  - light plane — bundle of mapped curved points forward intersection

Comparison of ranging methods

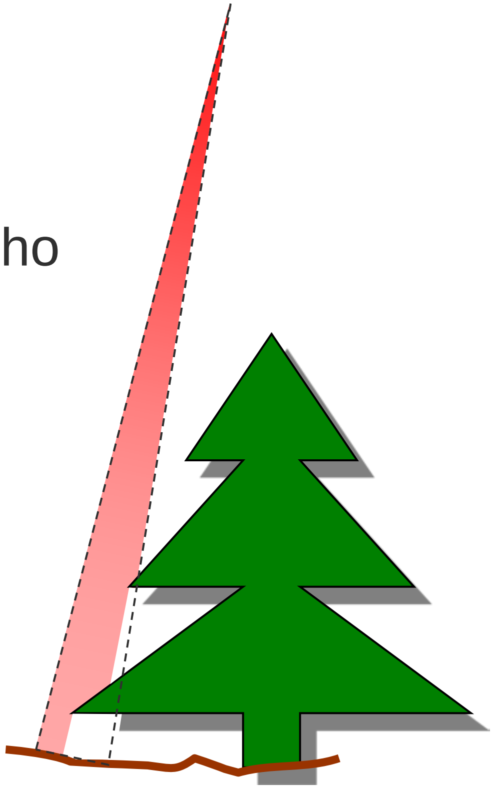
	Pulse round trip	Phase comparison	Triangulation
Maximum range	ALS: 1-5km TLS: 200-1000m	20-100m	0.5-2m
Sampling rate	ALS: 50-200kHz TLS: 1-15kHz	100-600kHz	~~50kHz
Precision	ALS: 1-10cm TLS: 5mm-3cm	1mm-5mm	0.01mm-0.5mm
	ALS + TLS	Only TLS	

LIDAR - LIght Detection And Ranging
Pulse Run Time – typically used in ALS



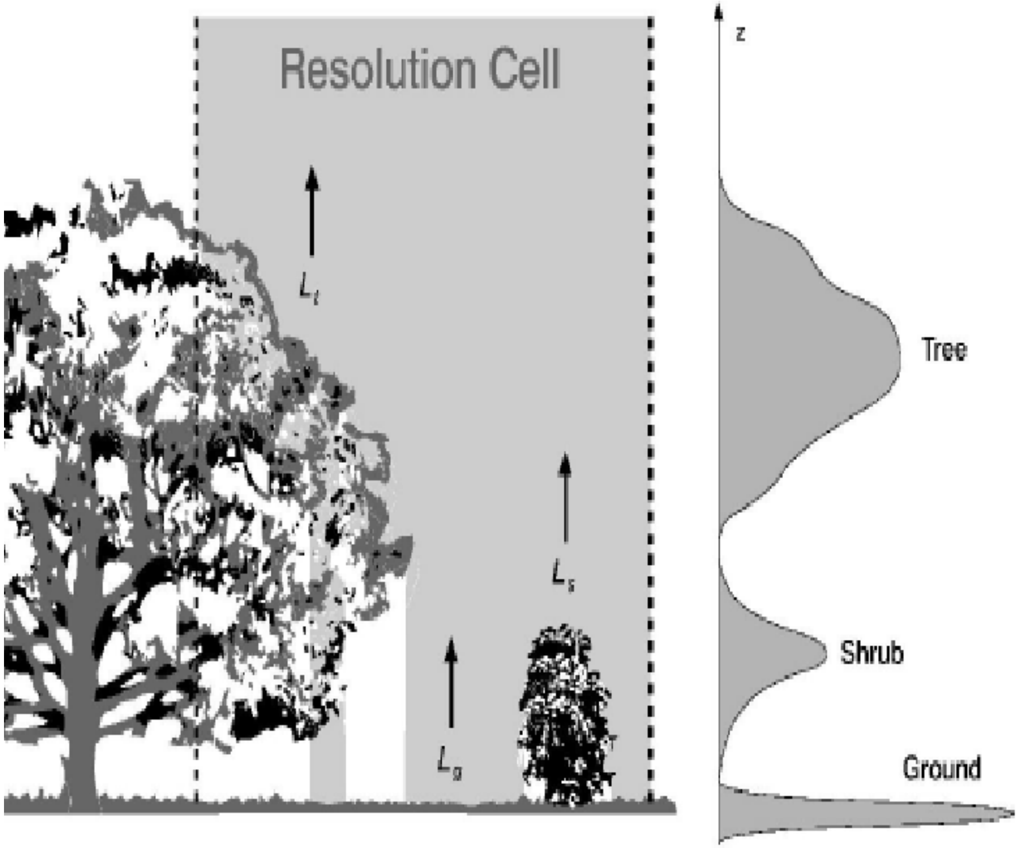
Multiple targets along the laser beam I

- Laser pulse has a certain energy distribution along (pulse length) and across (foot print area) the beam direction
- Within the beam: „instantaneous field of view“
  multiple different (area, linear, point) targets
  can be illuminated and can generate a „sensable“ echo
- One pulse can therefore generate multiple echos
  i.e.: first echo, intermediate echoes, last echo

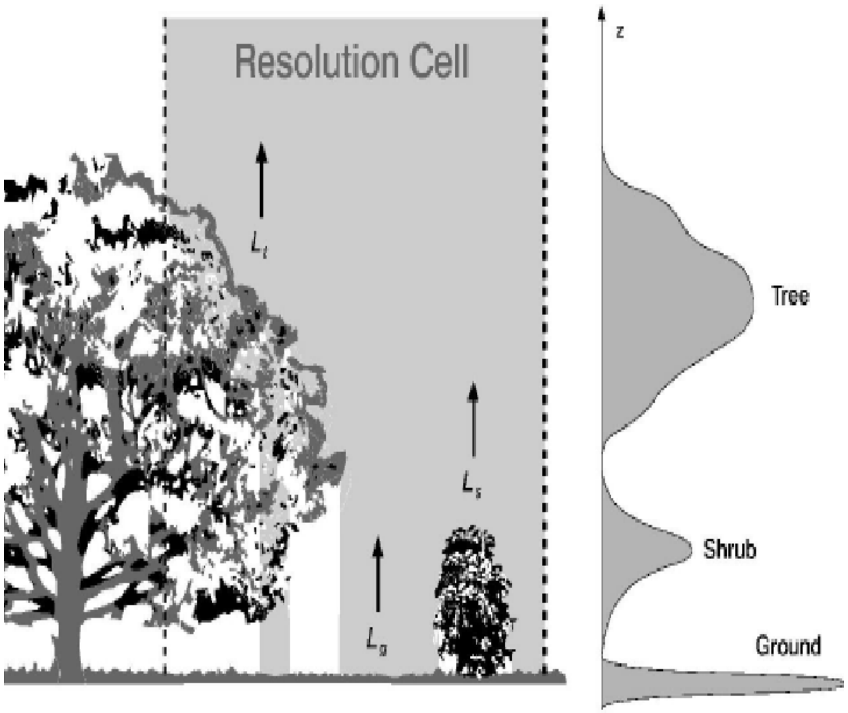


LIDAR – further developments I

Full-Wave-Form-Analysis

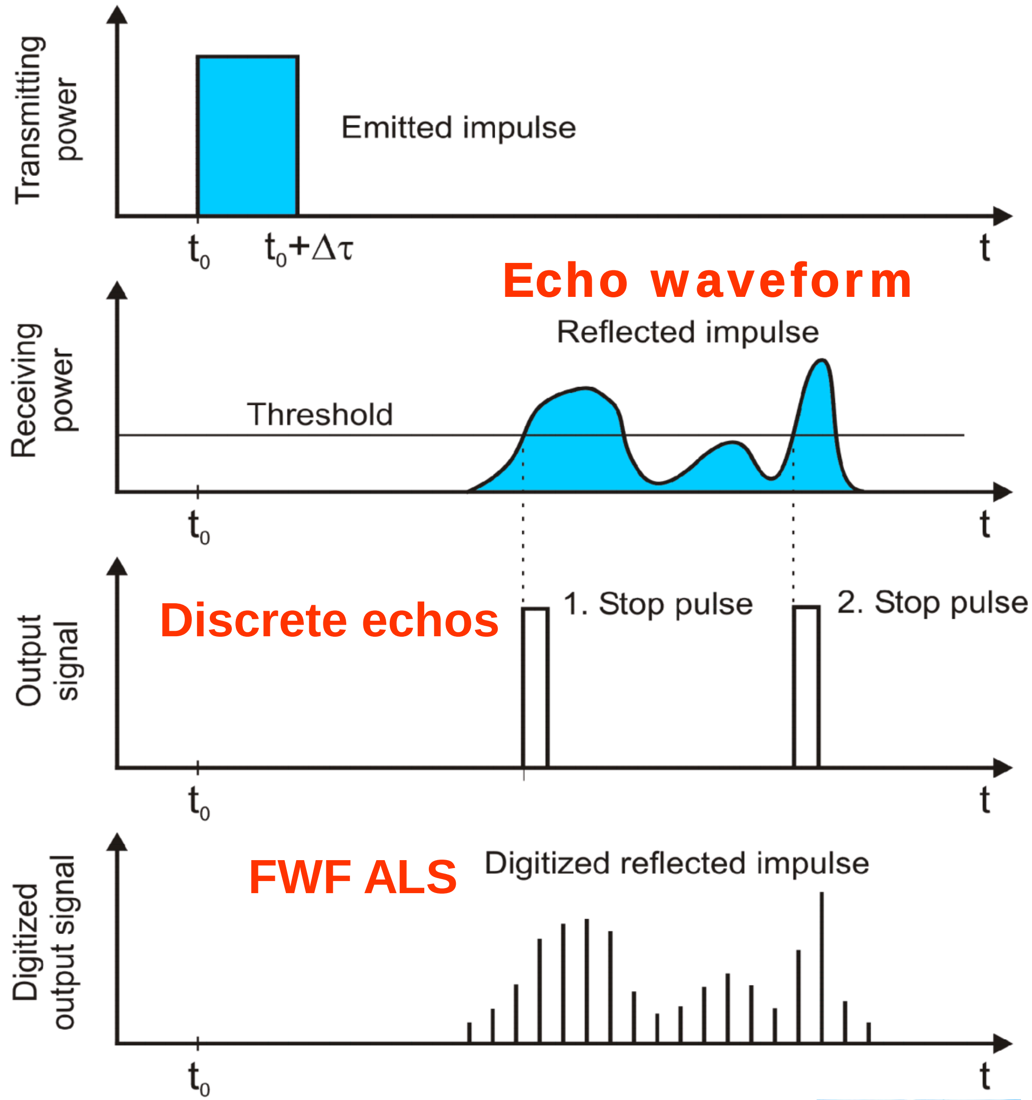


Discrete Echo vs. Full-Wave-Form LIDAR

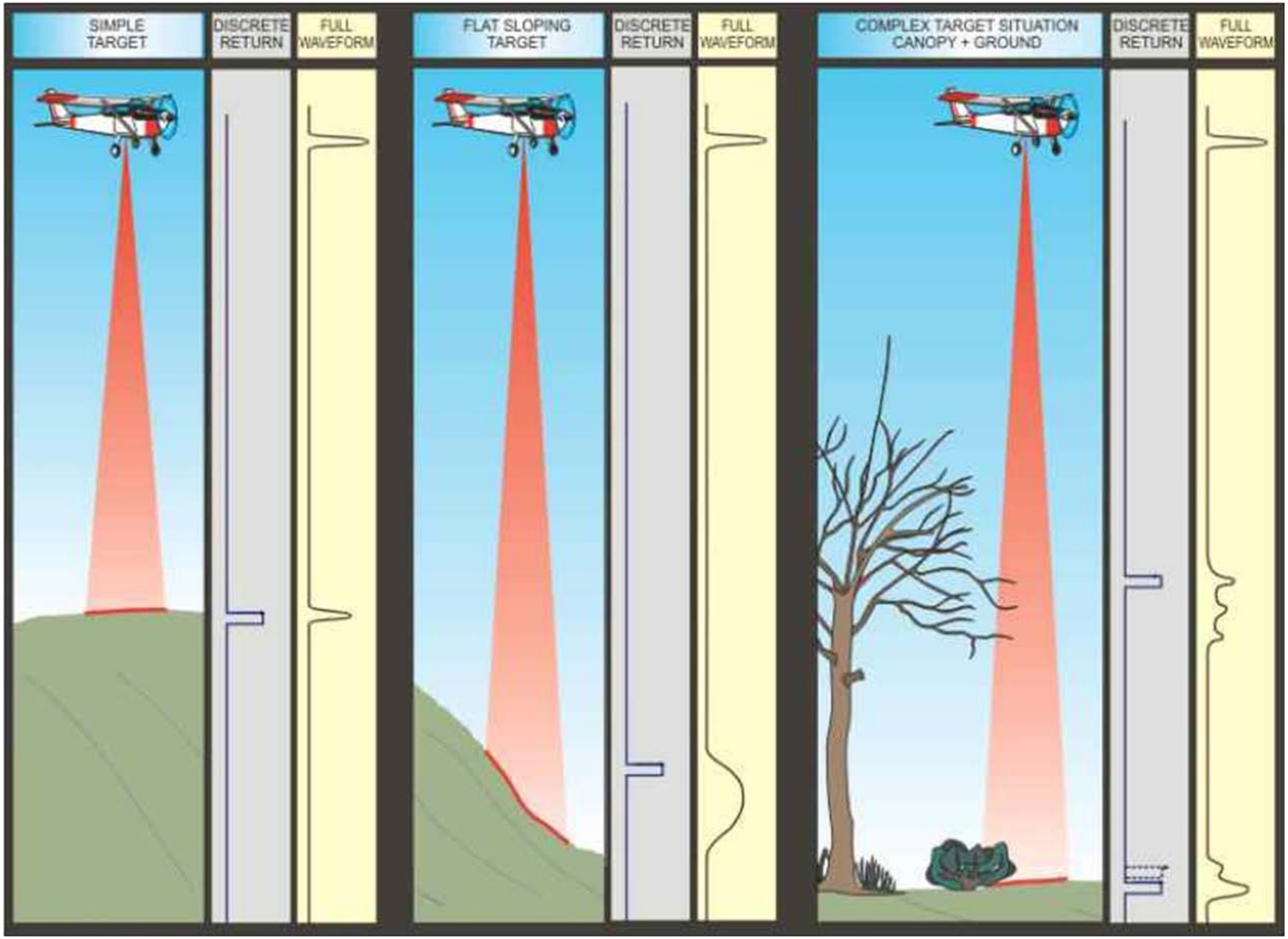


Laser foot print: ∅ ~ 0.2 – 3m

Acquisition of the all echos using a sampling interval of ~1 ns



Discrete Echo vs. Full-Wave-Form LIDAR



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Full-Wave-Form-Analysis in Postprocessing

- Gaussian decomposition:

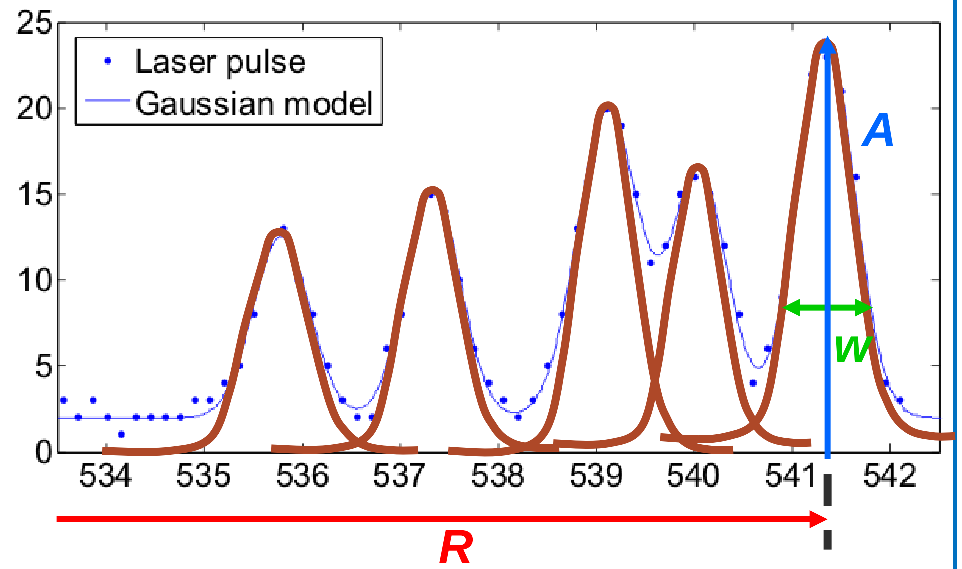
  Detection of echos by fitting Gaussian curves

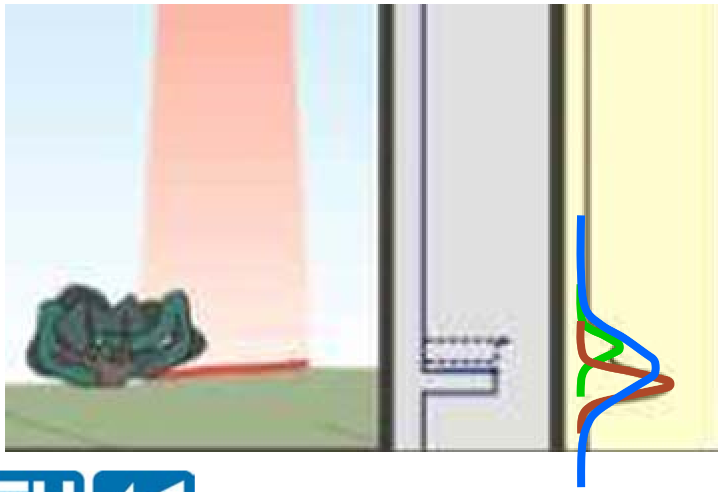
  → Information per echo:

  Amplitude (Intensity) A

  Range *R*

  Echo width *w*



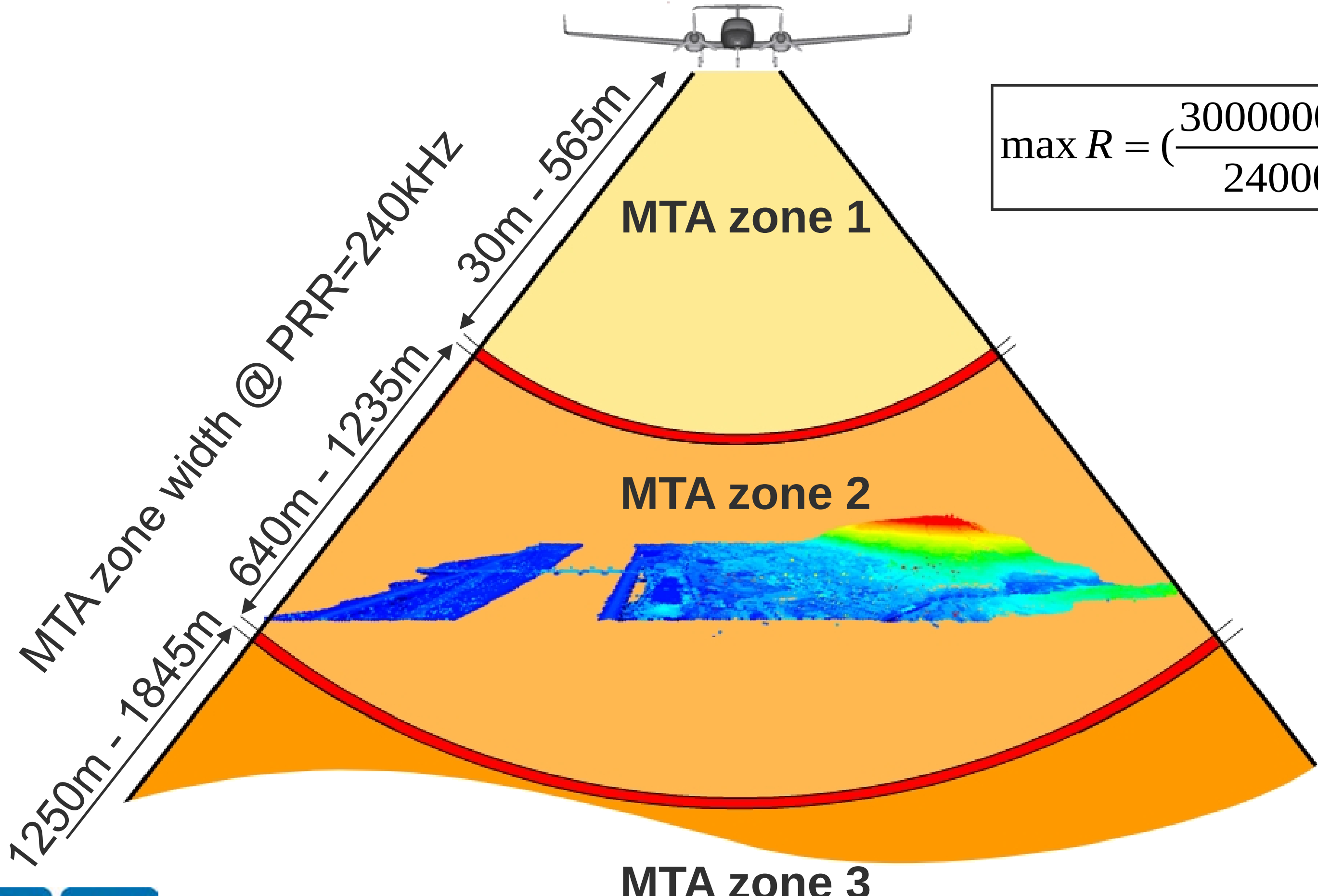


With FWF-Analysis the echos from the lower vegetation can be separated from the echos from the ground much better – or the mixted echo of both objects is detected because of its larger echo width.

→ Improvement of DTM compuation

LIDAR – further developments II

Multiple pulses in air



$$\max R = \left(\frac{300000000[m/s]}{240000[1/s]}\right)/2 = 625m$$

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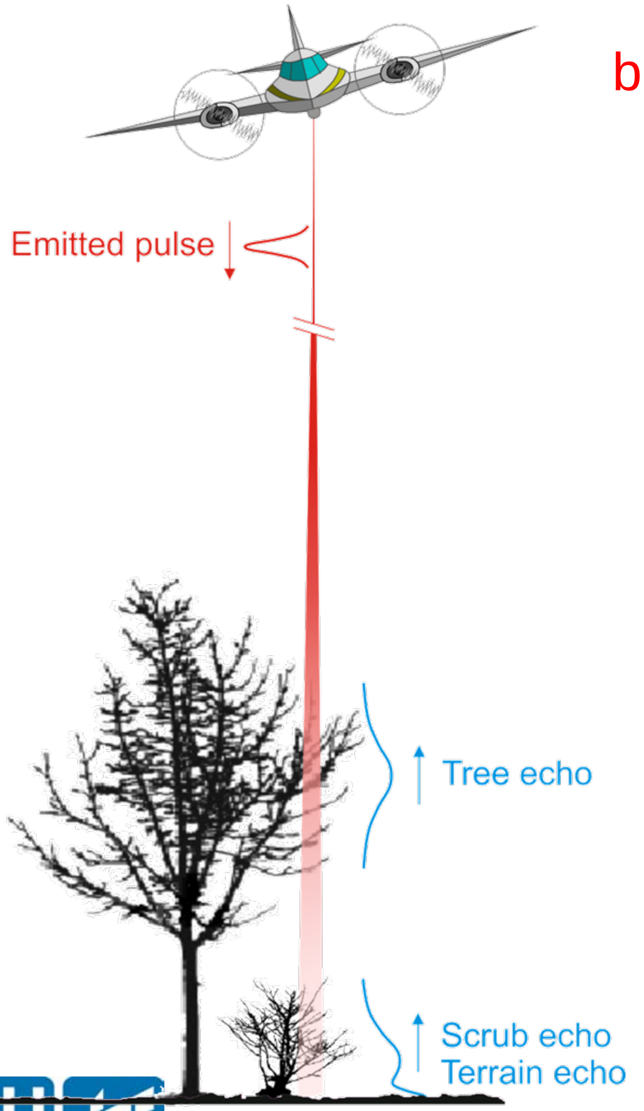
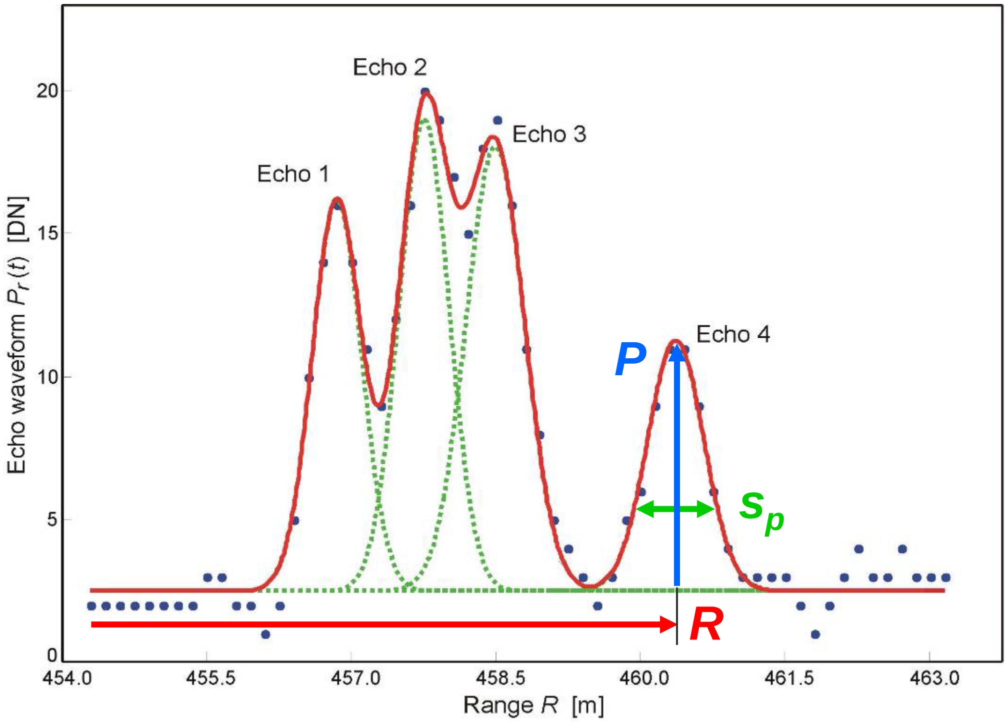
Radiometric Calibration I

besides geometric also radiometric information





Information per echo:

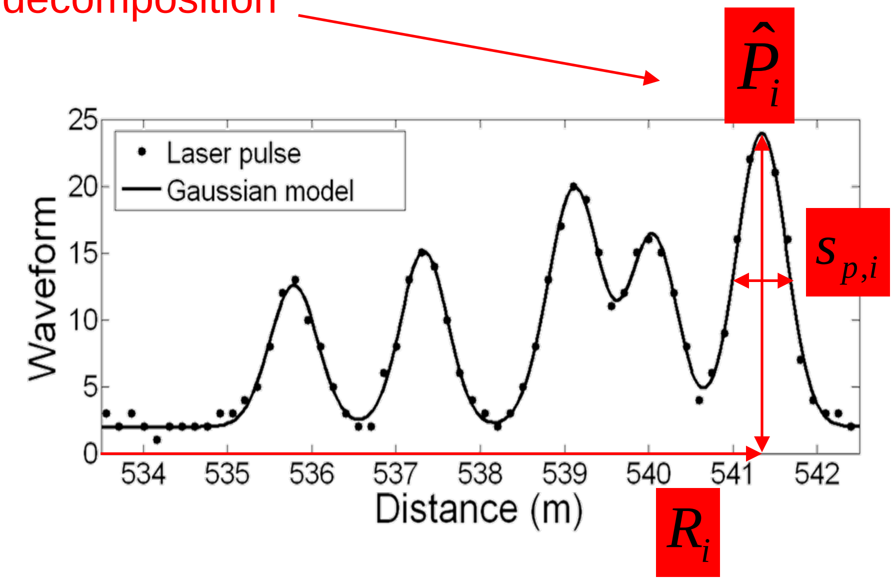
Amplitude (Intensity): *P* [DN]
Range: *R* [m]
Echo width: s_p [ns]

Radiometric Calibration II

from Gaussian decomposition

$$\sigma_i = \frac{4\pi \beta_t^2}{\eta_{atm}\,\eta_{sys} D_r^2 \hat{S} s_s} \cdot R_i^4 \hat{P}_i s_{p,i}$$

$$C_{cal}$$



$$\eta_{atm} = 10^{-2Ra/10000}$$

a ... Atmospheric attenuation coefficient (dB/km)

$$\sigma_{ref} = \pi \rho R^2 \beta^2 \qquad \rho = \rho_0 \cos\alpha$$

r ... reflectivity (0…1)

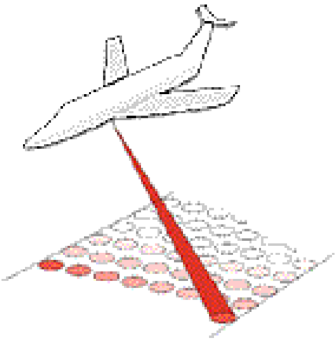
r_0 … reflectivity under 0° angle of incidence

a … angle of incidence

Surface Sampling – Scanning I

Different scanner mechanisms:

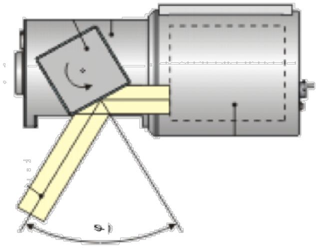
- Rotating one sided mirror (Fugro [1st system])
- Rotating prisma mirror (Riegl)
- Rotating inclined mirror (Z+F-Laser, Faro, 3rd-Tech)
- Pyramid mirror (Riegl)
- Oscillating mirror (Optech, Leica)
- Palmer scanner = nutating mirror (ScaLARS, NASA)
- Fiber scanner (TopoSys [1st systems])
- …



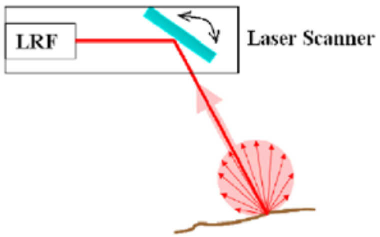
www.geolas.com

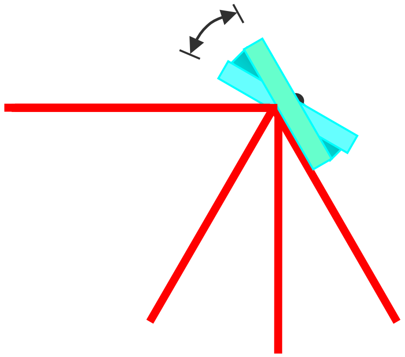
Surface Sampling – Scanning II

- Rotating mirror
  multiple facets

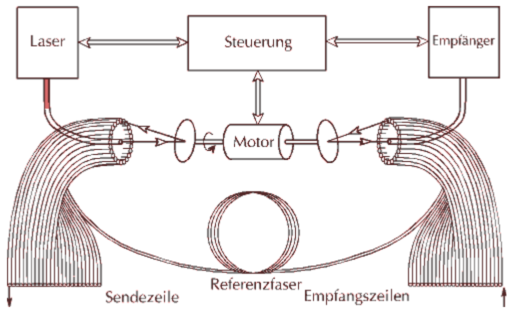


- Oscillating mirror

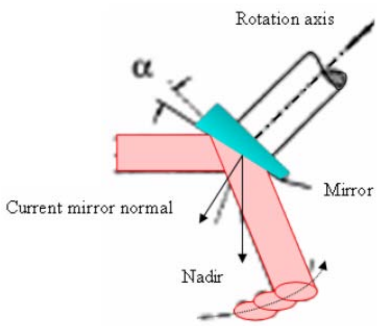




- Fiber scanner

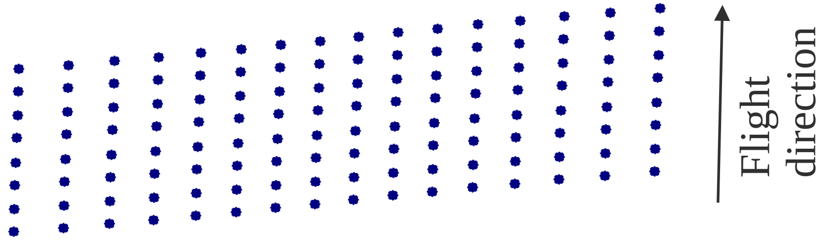


- Nutating mirror
  (Palmer Scanner)

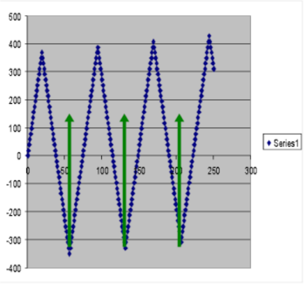


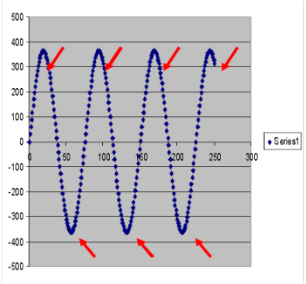
Surface Sampling – Scanning III

- Rotating mirror

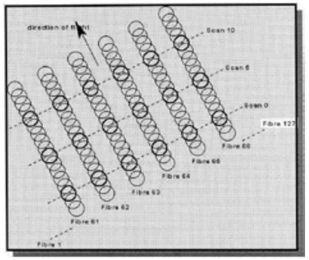


- Oscillating mirror

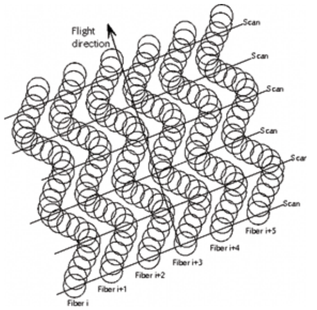




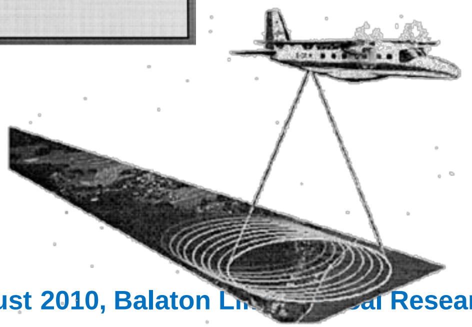
- Fiber scanner



or



- Nutating mirror



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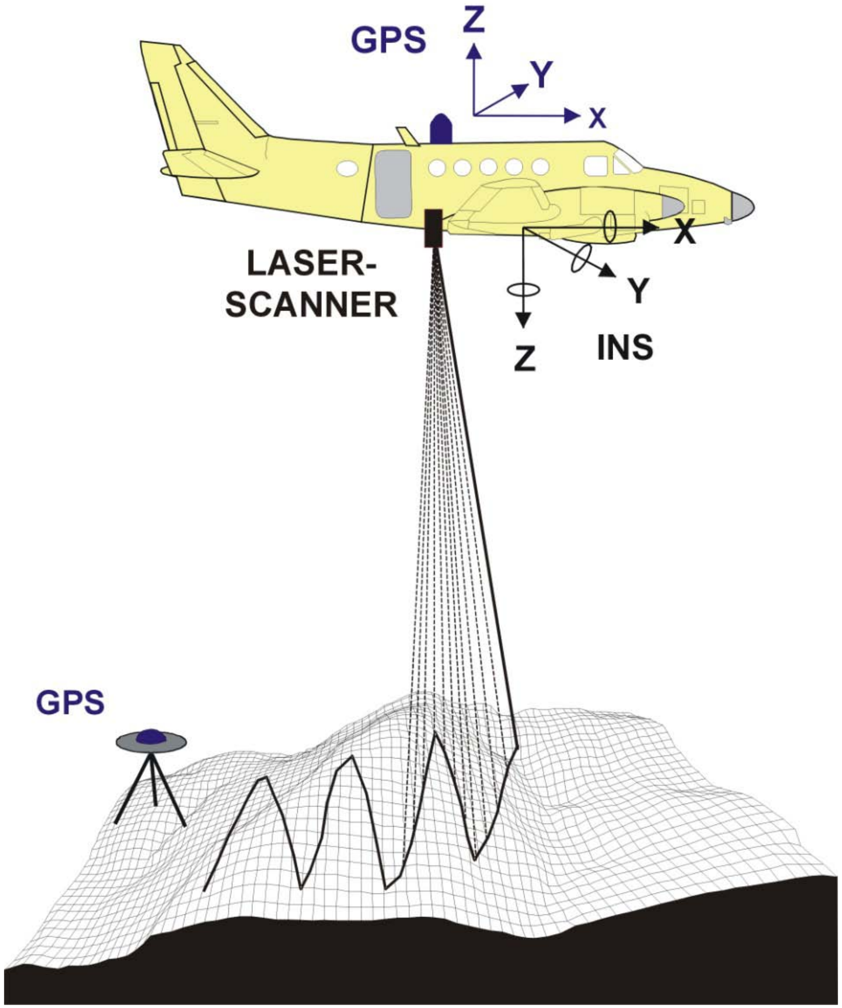
Airborne Laser Scanning (ALS) Sensors

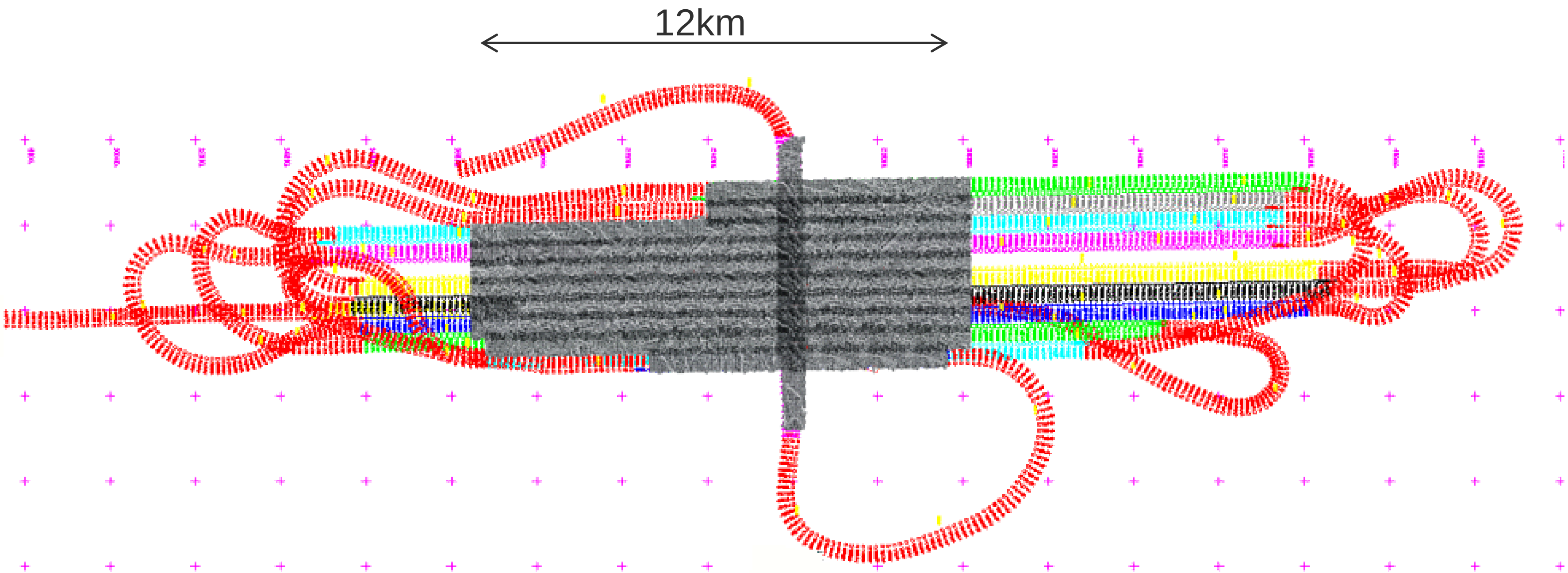


Technical data of typical ALS Systems:

Specification	Typical Value
Wavelength	1.0 and 1.5μm
Pulse Duration	5-15ns
Beam Divergence	0.2-2mrad
Pulse Repetition Rate	1-266kHz
Field of View	14-75°
Scan Rate	25-650Hz
Scan Pattern	Zigzag, parallel, elliptical, sinusoidal
Footprint	0.25-2m
Multiple Returns	2-8 or full-waveform
Intensity	Yes
Operating Altitude	300-5000m
GPS Frequency	1-2Hz (max. 10 Hz)
INS Frequency	128-1000Hz
Accuracy (elevation)	0.10cm
Accuracy (planimetric)	10-100cm

ALS data acquisition

Strip-wise data acquisition

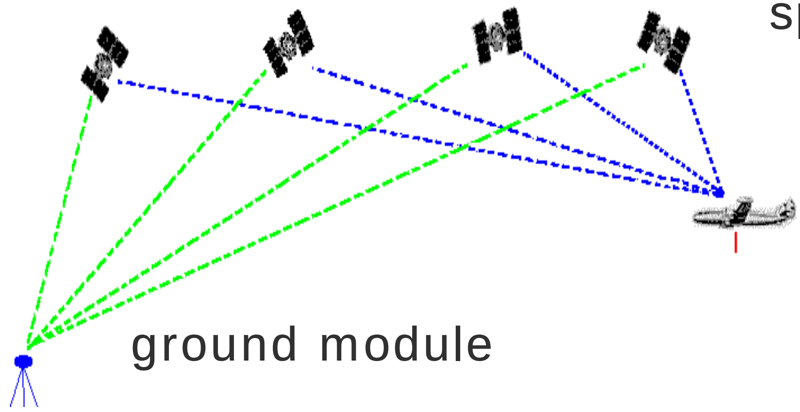


Neighbouring strips have to overlap!

→ Complete acquisition of the planned area

→ Redundant observation, Quality Control

Georeferencing – exterior orientation



- Airborne Laser Scanning
  - is a *dynamic (kinematic)* data acquisition method.
- For every observation pair (range, angle) that is observed per echo the
  - position (x,y,z) in space, and the
  - angular attitude (ω,φ,κ)
  - of the sensor system have to be konwn.
- E*xterior orientation* - by a Position and Orientation System (POS)
  - GNSS (Global Navigation Satellite System)
  - IMU (Inertial Measurement Unit)

Aerial Module: Airborne Laser Scanner System

Airborne laser scanning uses a **multi sensor system** (MSS) with these components:

- Laserscanner
  - range measurement (LiDAR)
  - angle measurement
- GNSS reciever
  - measures position of the plattform
- IMU (Intertial Measurement Unit)
  - measures rotation of the plattform
- synchronisation using the GNSS-Signal

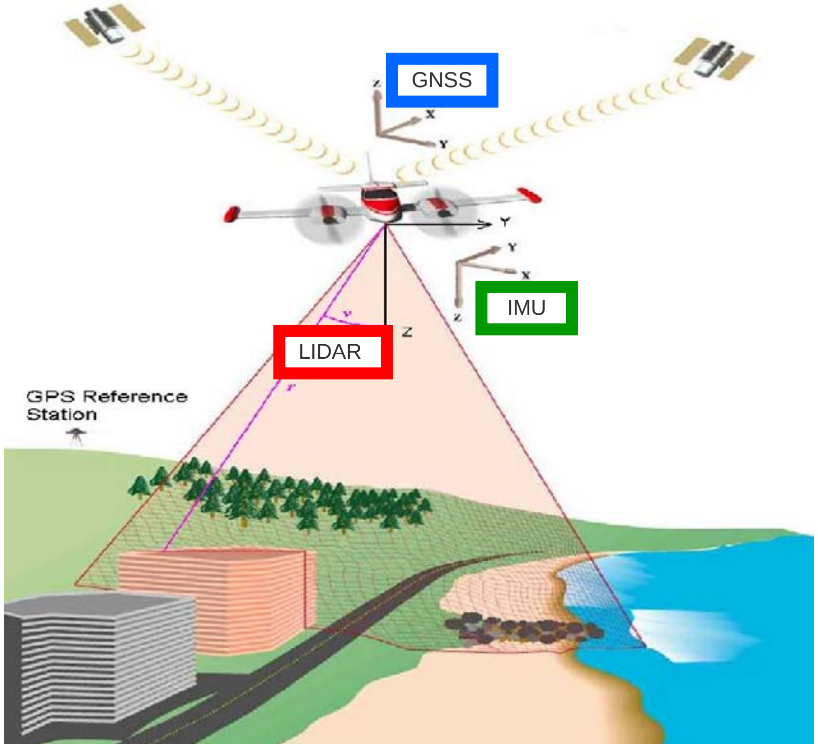
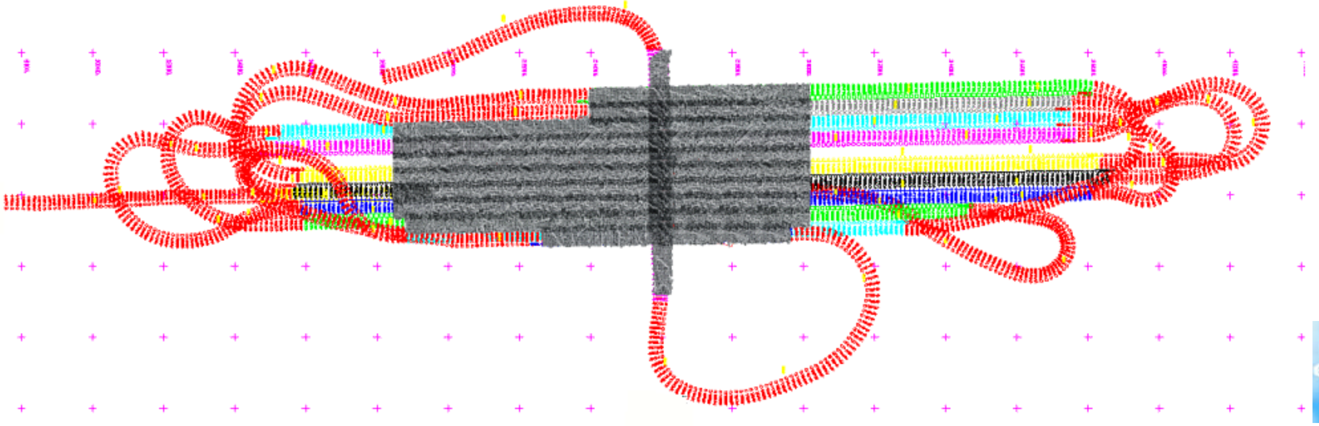


Figure: Optech

- strip-wise data acquisition:



GNSS – Global Navigation Satellite System

- Purpose:
  - navigation
  - positioning of the LS-sensor
  - synchronization of measurements !
- Instrument:
  - antenna on top of aircraft
  - receiver inside
  - Ground module
- Method:
  - kinematic differential GNSS
- Measurment frequency: 1-10Hz
- Absolute Precision:
  - Planar: ±5-10cm
  - Height: ±10-15cm

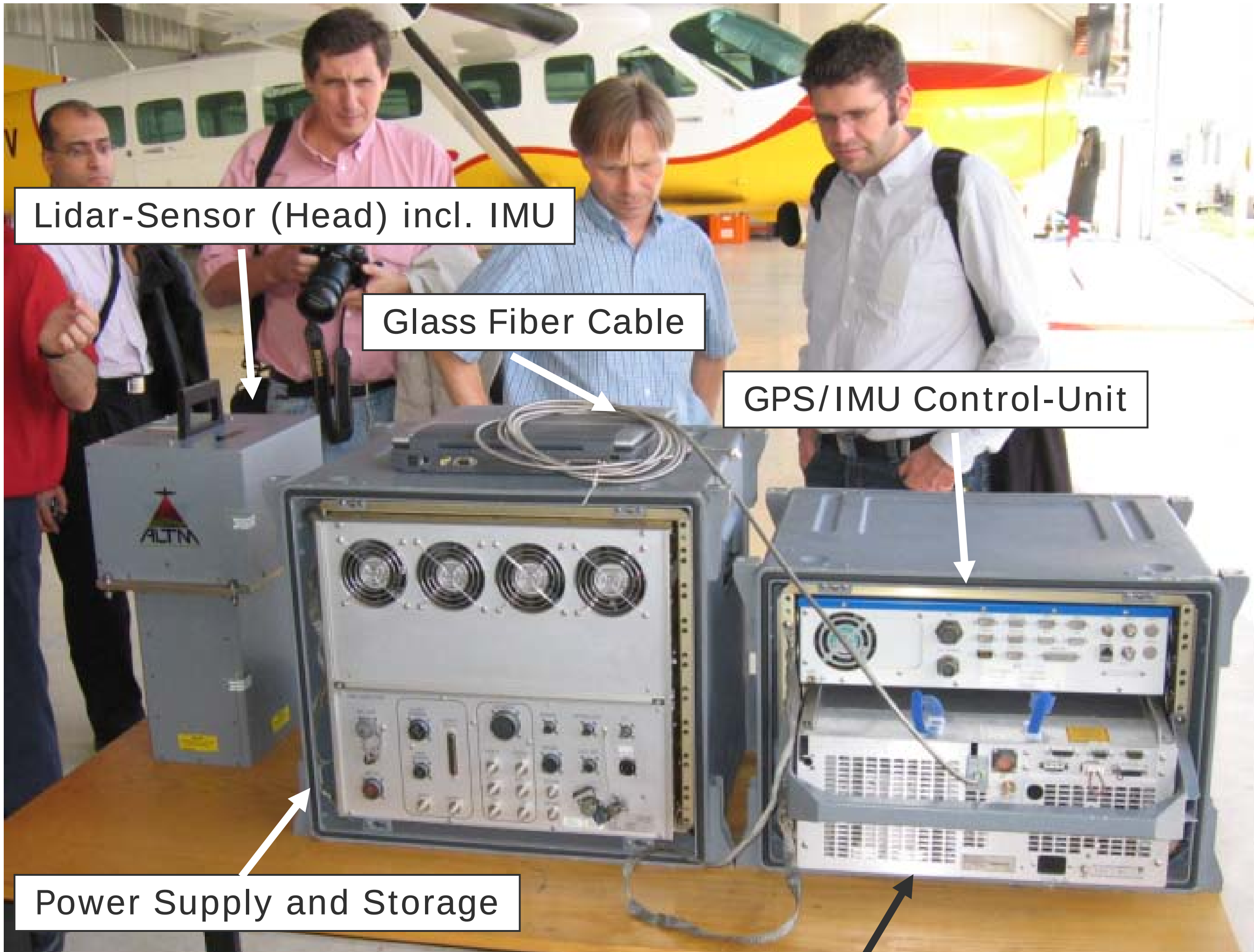
IGI, AEROcontrol

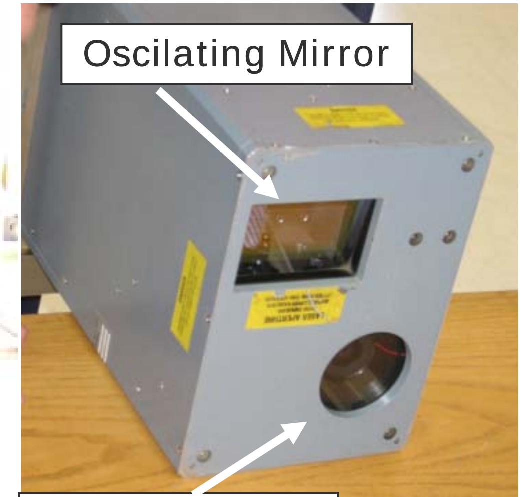
Inertial Measurement Unit (IMU)

- Purpose: attitude determination of the sensor platform
- Instruments: gyroscopes and accelerometers
- Measures: angular and acceleration increments
- Method: integration of observations
- Frequency: 100-1000 Hz
- Precision: ±0.005-0.03°
  … ±9-50cm @ 1000m

Applanix POS-AV IMU

ALS-System

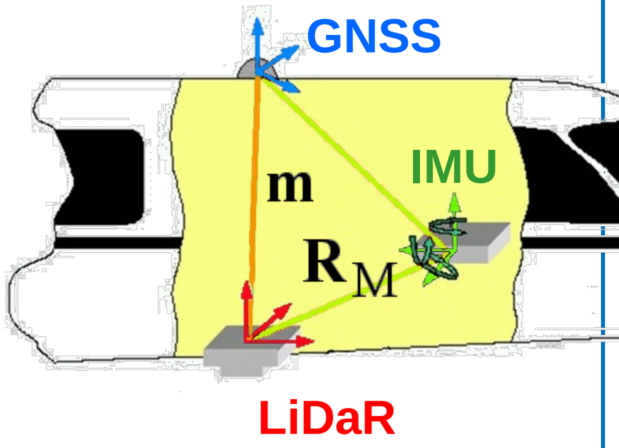

Lidar-Sensor (Head) incl. IMU
Glass Fiber Cable
GPS/IMU Control-Unit
Power Supply and Storage
Laser Generator and Processor


Oscilating Mirror
Digital Camera


GPS Antenna

Mathematical model for ALS – Direct Georeferencing

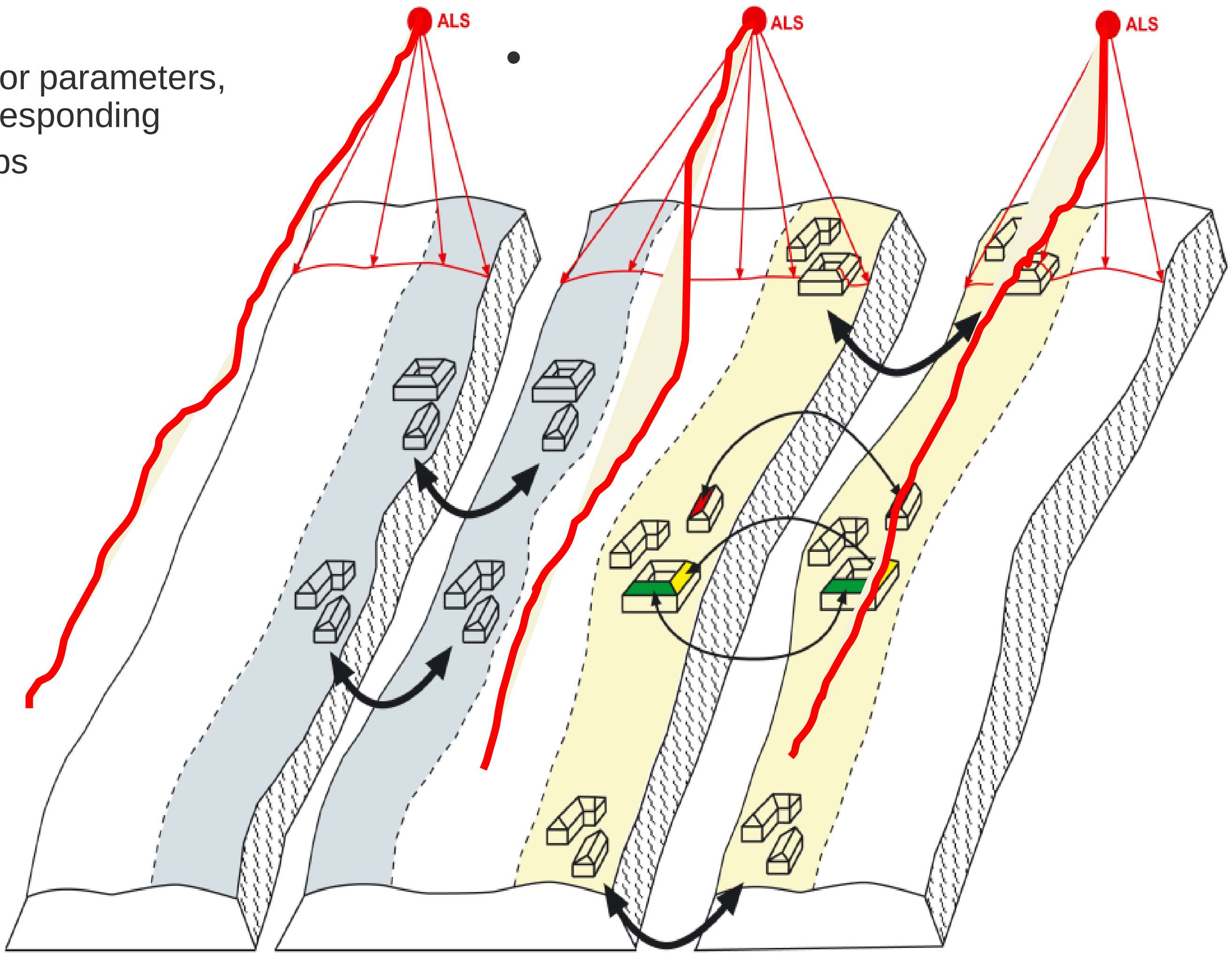
$$\mathbf{X} = \mathbf{X}_{GNSS} + \mathbf{R}_{IMU} \cdot \left(\mathbf{m} - \mathbf{R}_M \cdot \begin{pmatrix} 0 \\ \rho \cdot \sin\theta \\ \rho \cdot \cos\theta \end{pmatrix} \right)$$



$\mathbf{X}$	Surface point (in the reference system)
$\mathbf{X}_{GNSS}$	GNSS antenna: phase centre
$\mathbf{R}_{IMU}$	Rotation from “sensor body frame” to reference system
ρ, θ	Range and deflection angle of the laser beam
$\mathbf{m}$	Mounting offset vector (‘lever arm’)
$\mathbf{R}_M$	Mounting rotation bias (‘misalignment’)

Improving the Georeferencing of the ALS strips

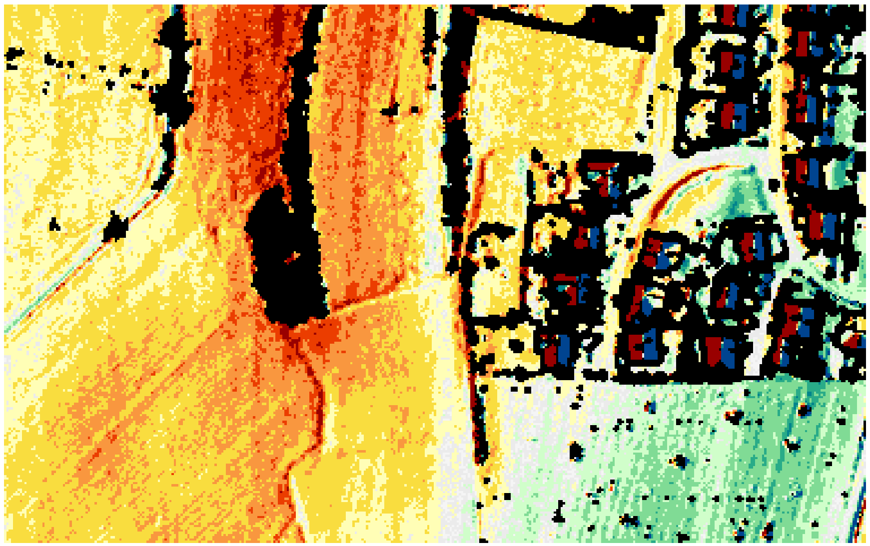
Shift and rotate the strips,
thereby correcting internal sensor parameters,
so that the discrepances at corresponding
Planes in the overlap of the strips
are minimized.

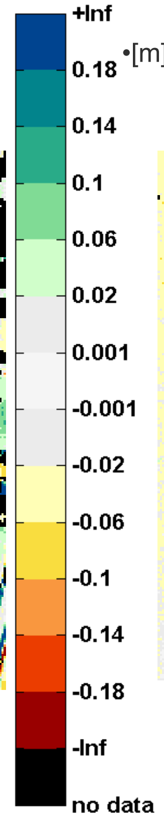


H. Kager: "Discrepancies Between Overlapping Laser Scanning Strips-Simultaneous Fitting of Aerial Laser Scanner Strips"; ISPRS XXth Congress, Istanbul; 2004

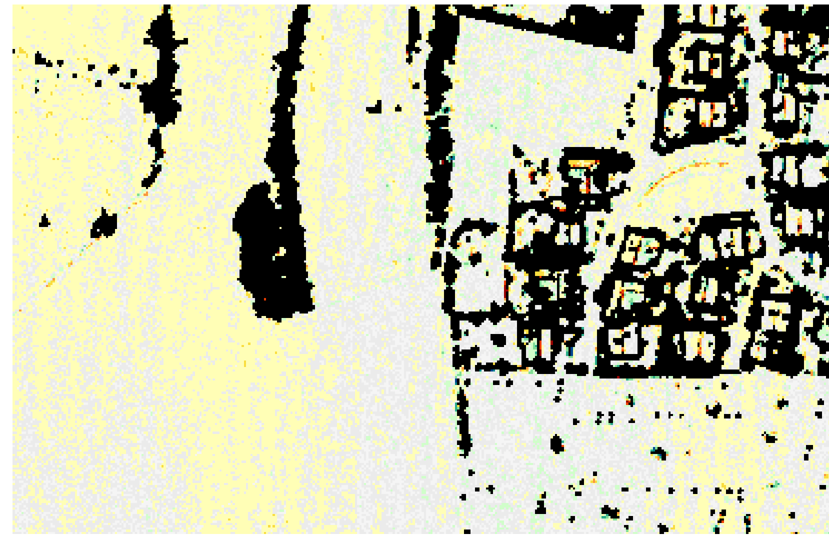
Improving the Georeferencing of the ALS strips

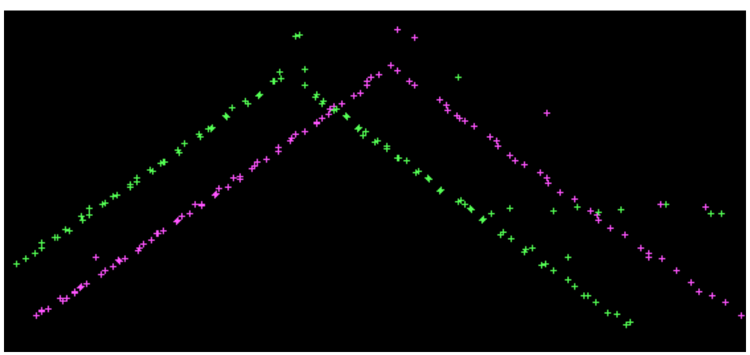
Original:



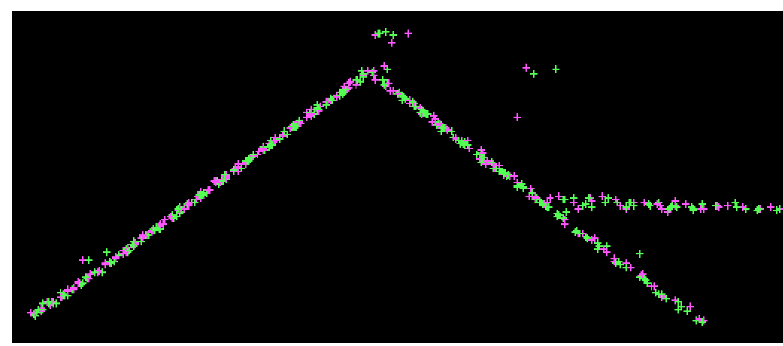


Improved:





In cooperation with Vermessung Wenger-Öhn & AVT



Example: Main

- 62 strips, east-west, 10 x 17 km²
- no GNSS/IMU trajectory available
- aim: extraction of hydrologic structure lines
- Quality control of the geometry of the delivered data:

RMS(X)	RMS(Y)	RMS(Z)
59.3	23.4	4.5

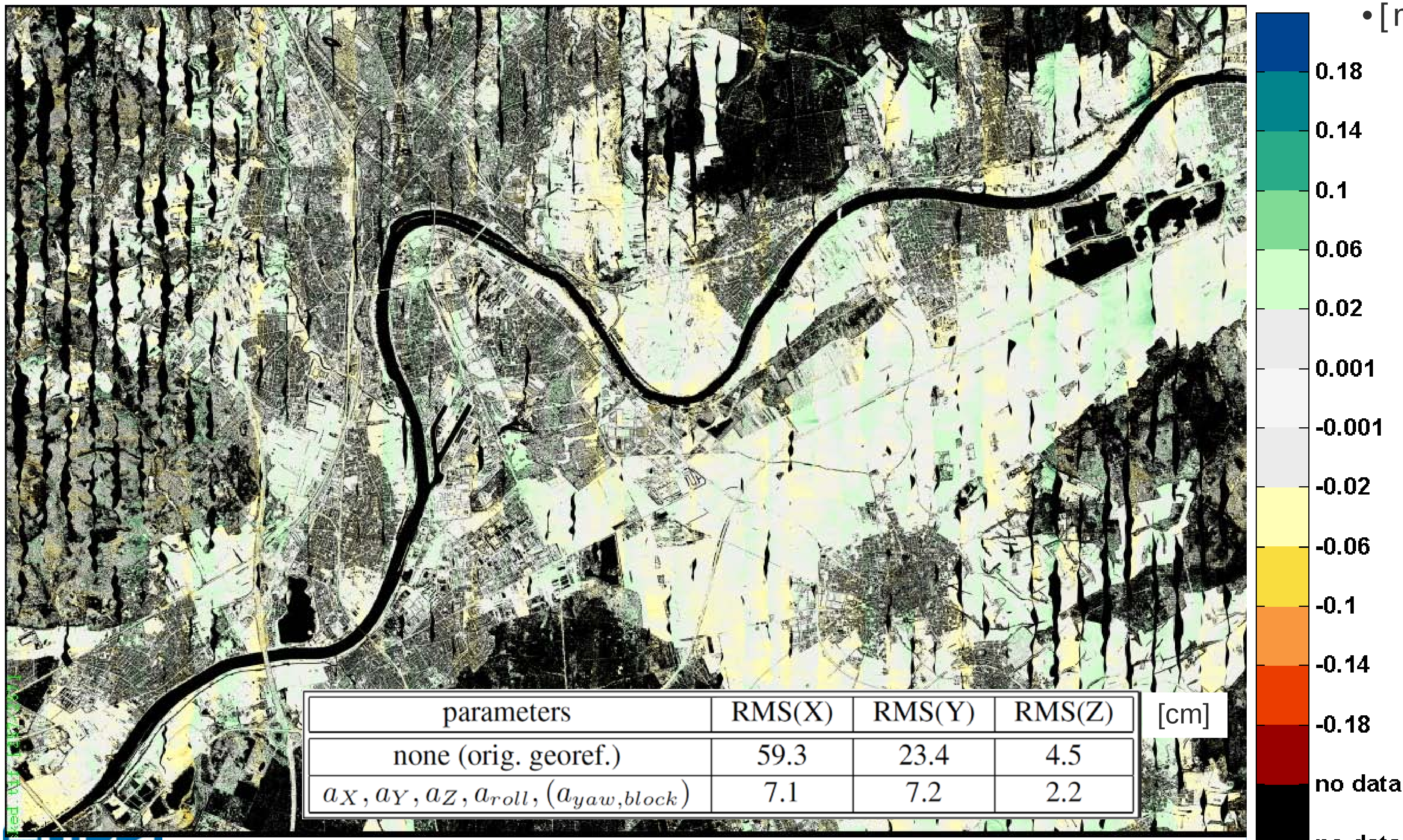
[cm]

→ **strip adjustment necessary**

- measuring of corresponding points using LSM (ca. 25 points per strip)
- homogenous and dense point distribution is important
- different sets of parameters (A–D)

Example: Main – before strip adjustment

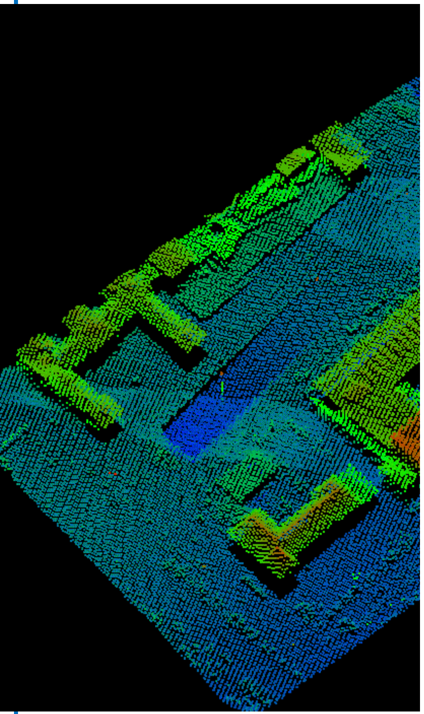
Example: Main – after strip adjustment

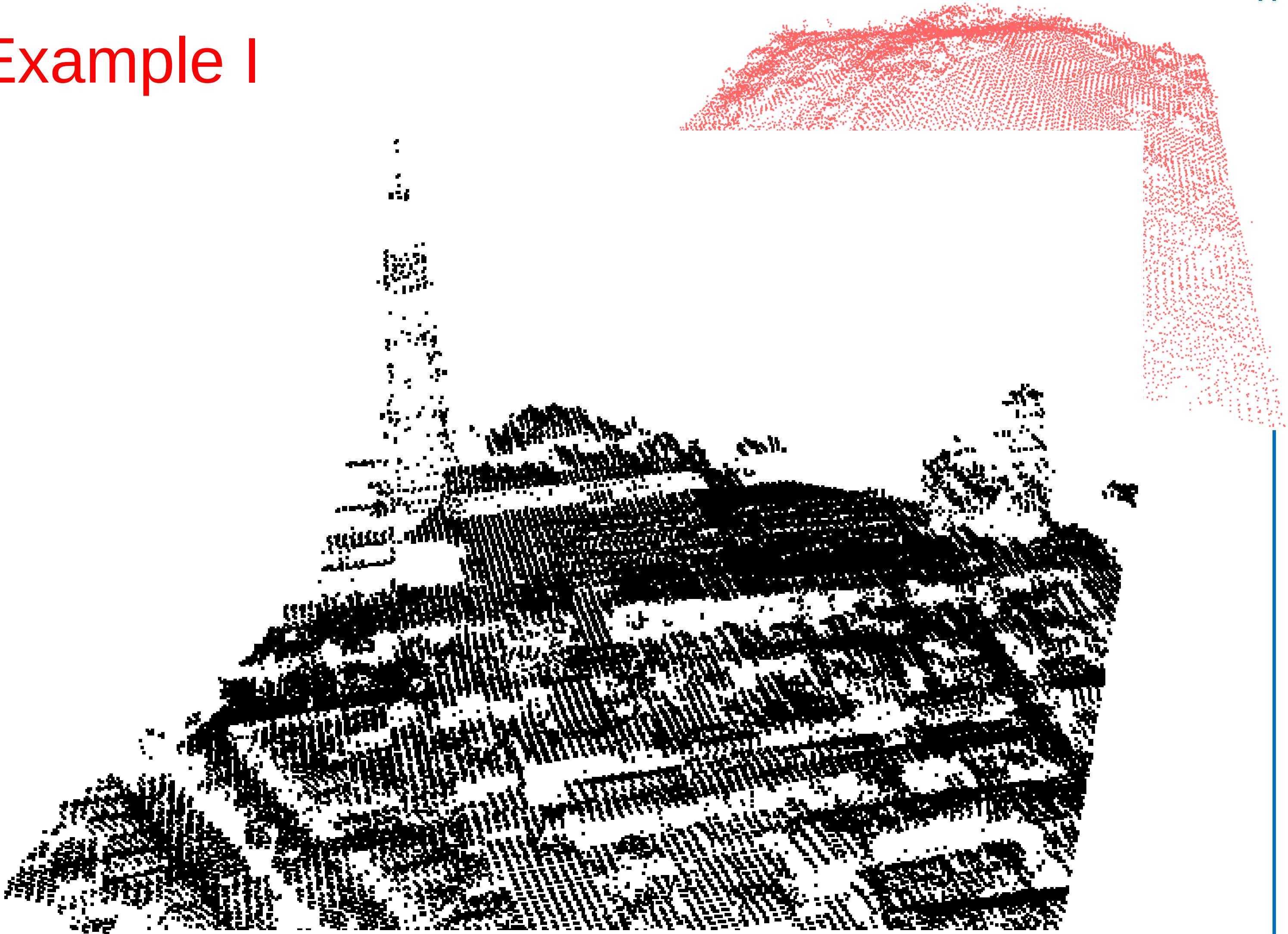


parameters	RMS(X)	RMS(Y)	RMS(Z)
none (orig. georef.)	59.3	23.4	4.5
$a_X, a_Y, a_Z, a_{roll}, (a_{yaw,block})$	7.1	7.2	2.2

[cm]

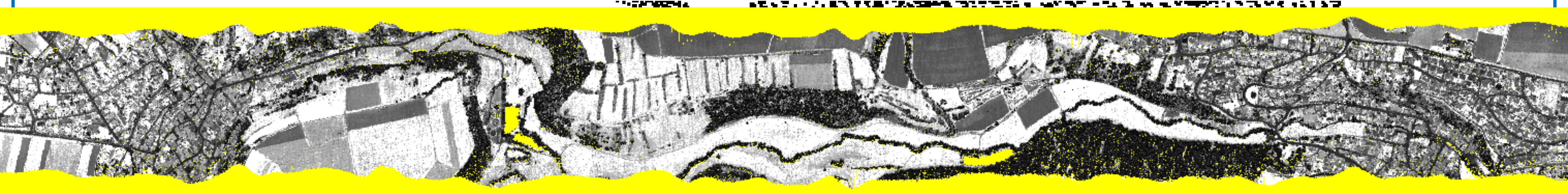
ALS Data Example I



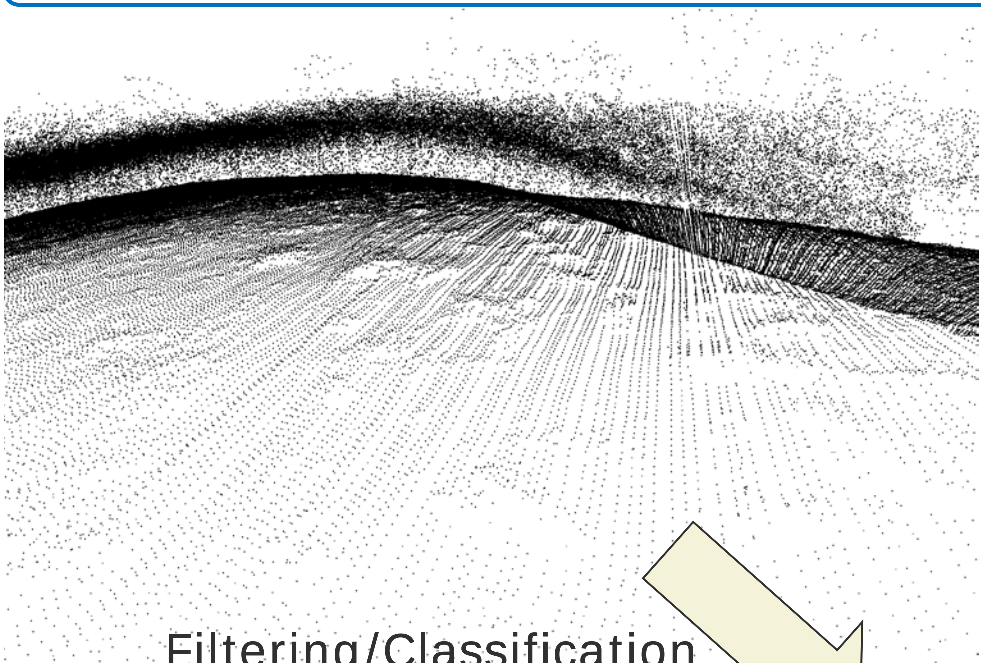


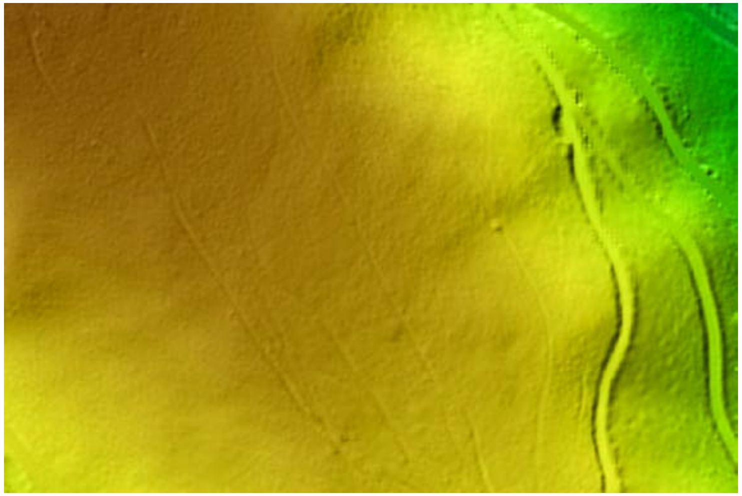
"3D point cloud"

Strip wise data acquisition in airborne laser scanning



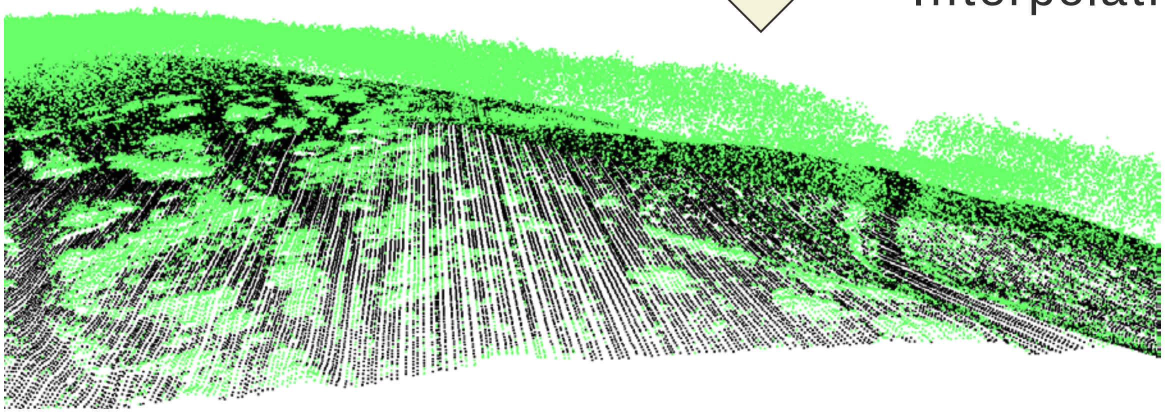
ALS Data Example II



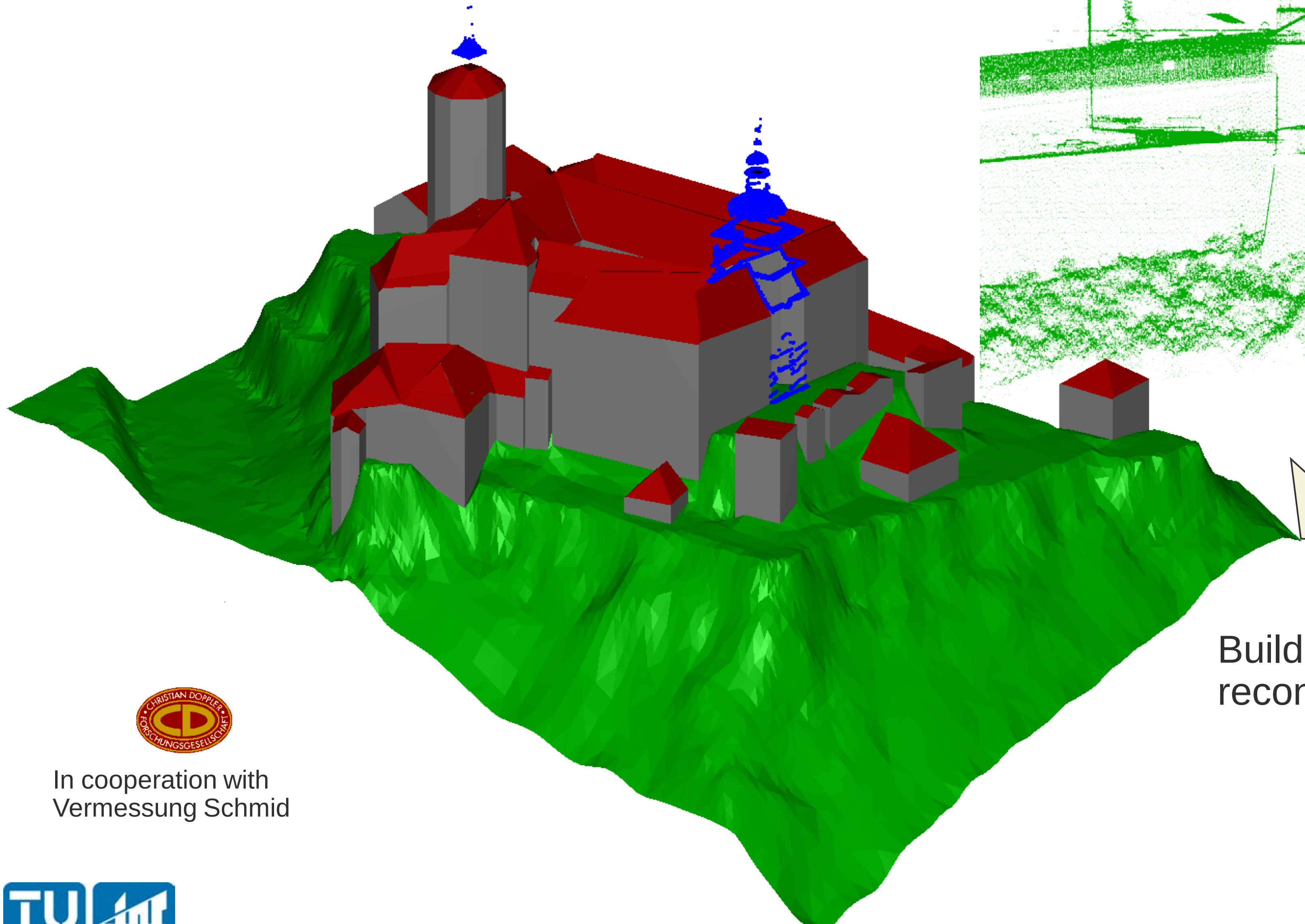


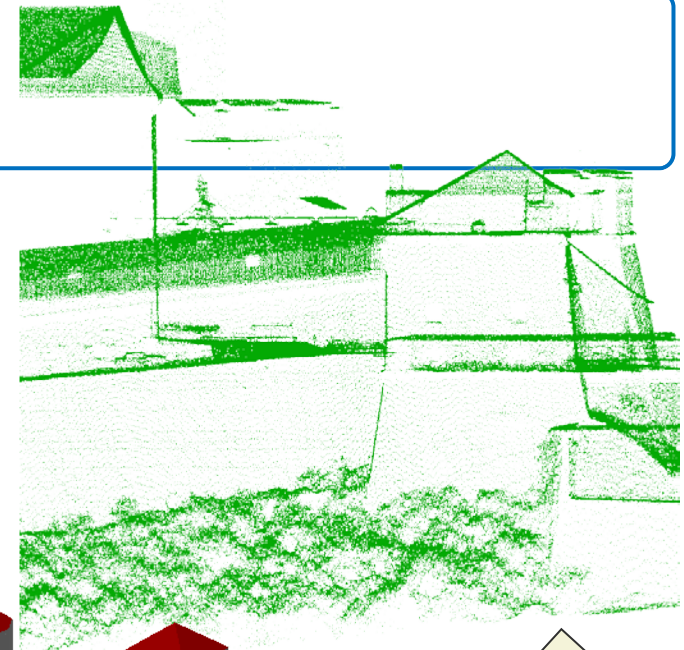
Filtering/Classification

Interpolation of a DTM



ALS Data Example III



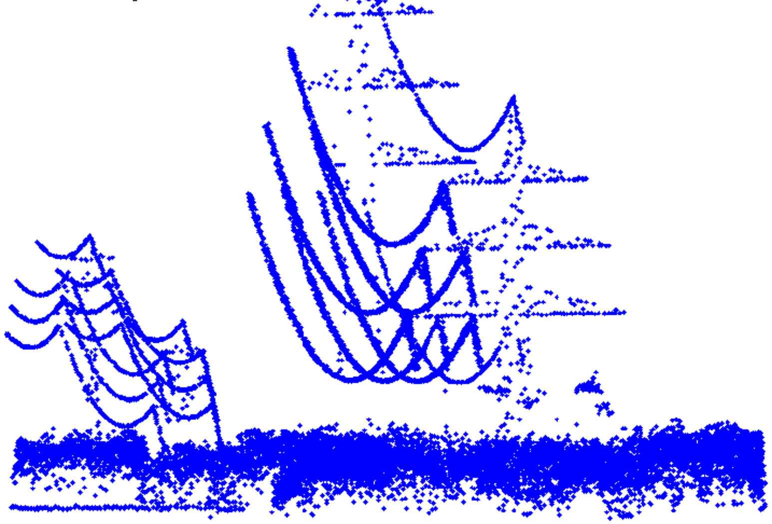


Building model reconstruction

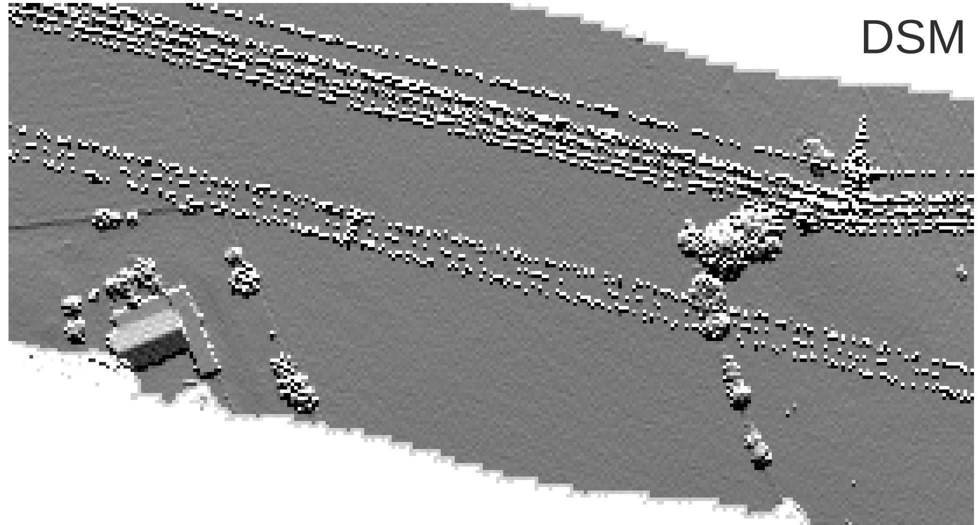
In cooperation with
Vermessung Schmid

ALS Data Example IV

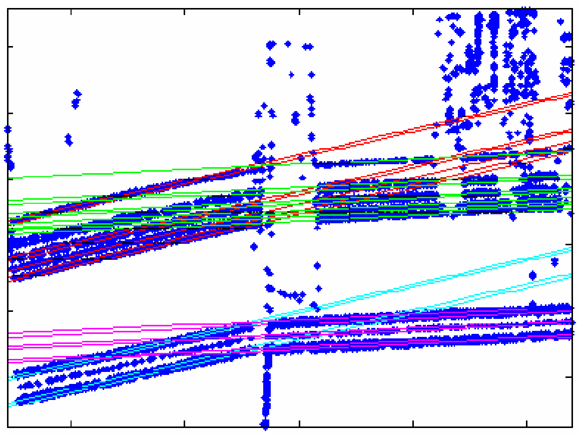
ALS-points

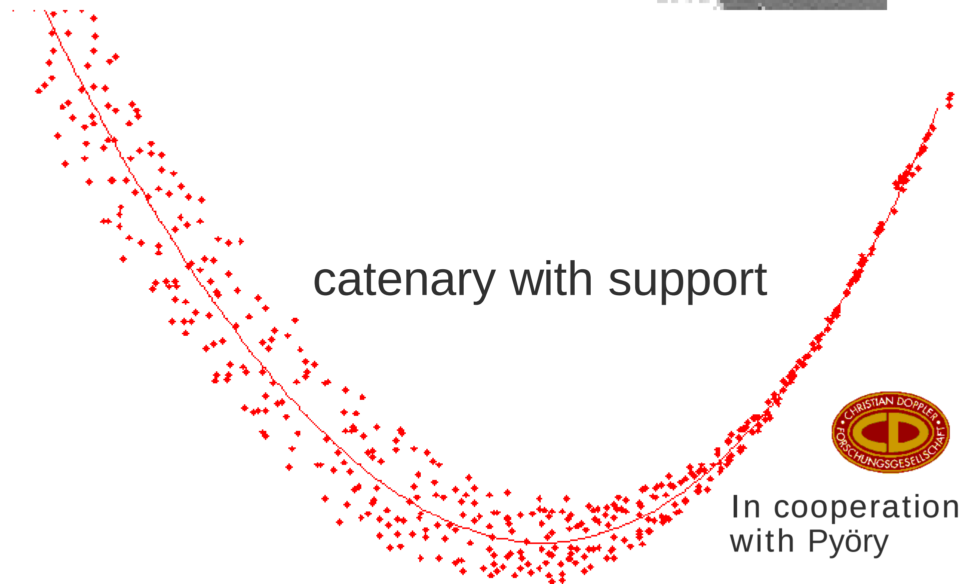


DSM



Lines via Hough transformation

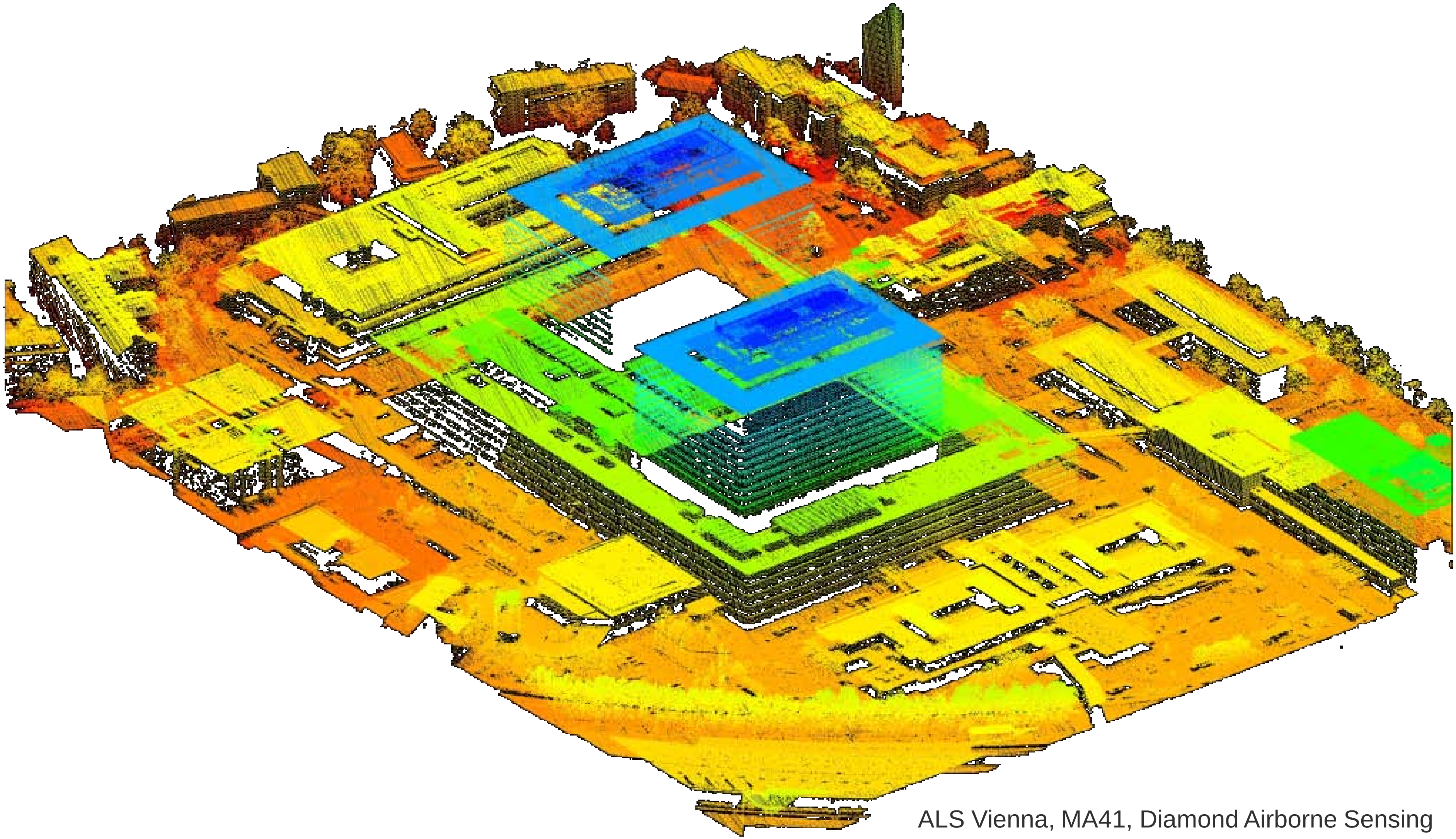




In cooperation with Pyöry

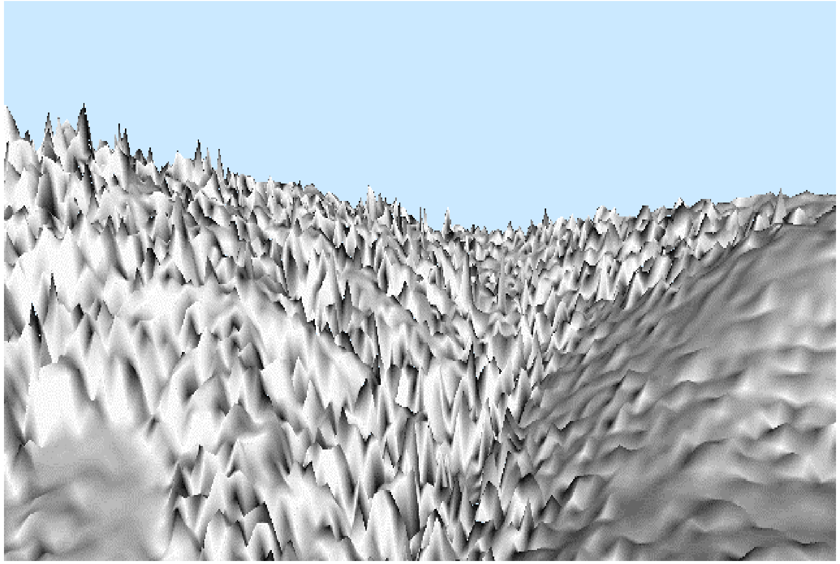
Melzer, T. and Briese, C., Extraction and Modeling of Power Lines from ALS Point Clouds, OAGM, 47-54, 2004, Österreichische Computer Gesellschaft

ALS Wien 2006/2007

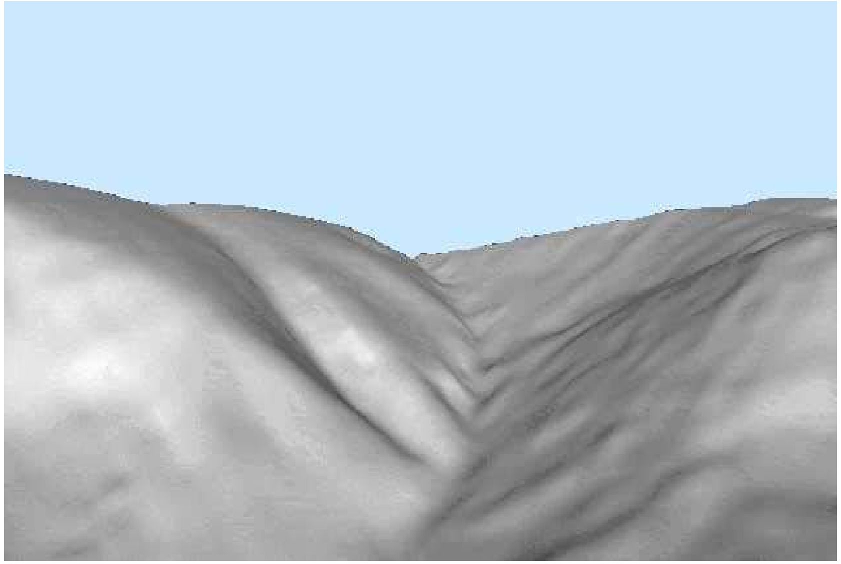


ALS Vienna, MA41, Diamond Airborne Sensing

Digital Surface and Terrain Models



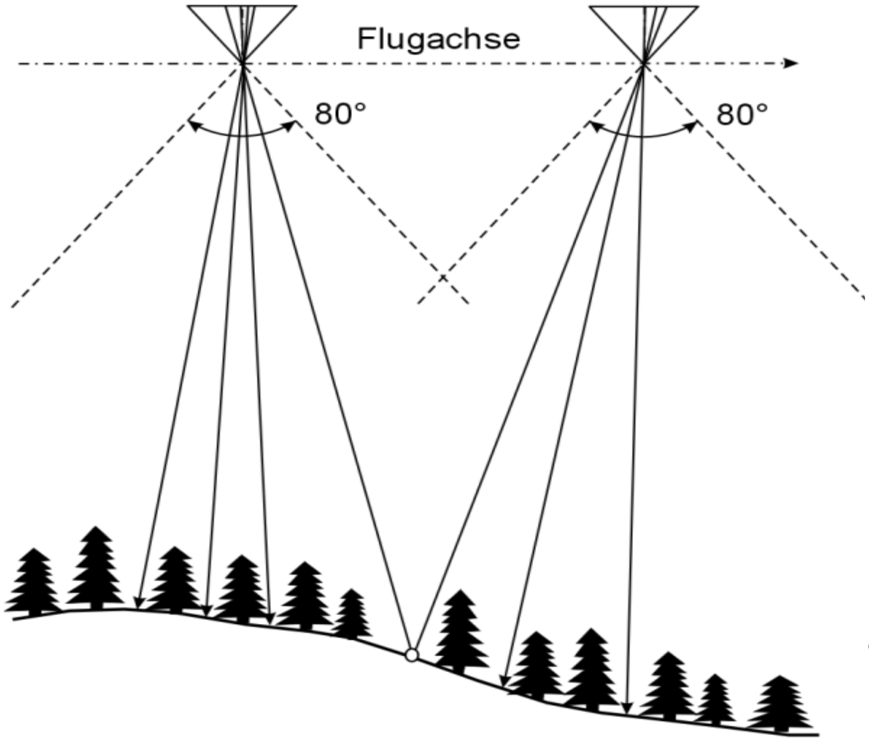
DSM



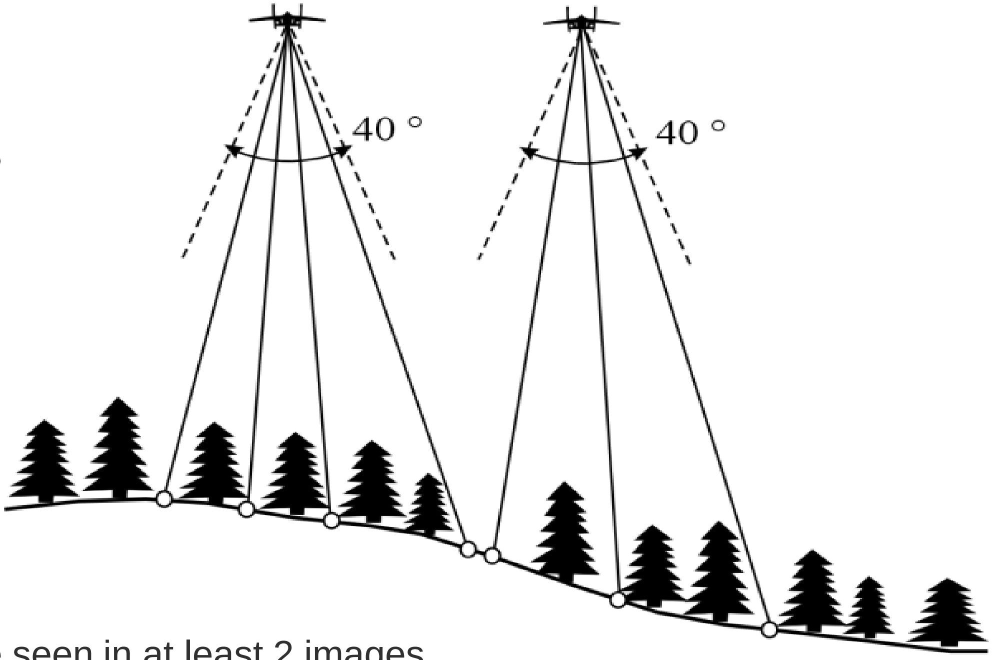
DTM

Terrain Models

Airborne Photogrammetry



Airborne Laser Scanning



Photogrammetry: Forest floor must be seen in at least 2 images

→ 2x "direct visibility" required
→ not possible in general because of the trees

Laserscanning: 1x "direct visibility" is sufficient (even partly visible → Last-Echo)

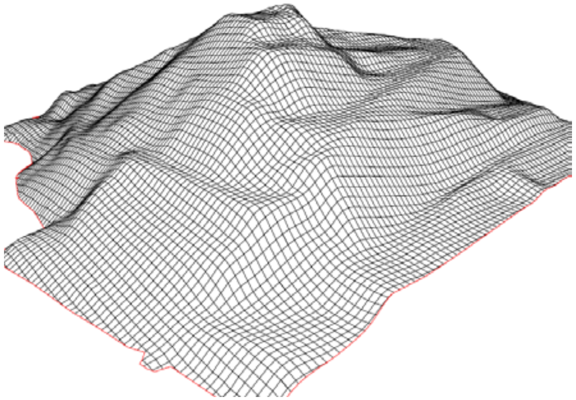
Digital Terrain Model - DTM

Digital representation and storage of the model via terrain heights

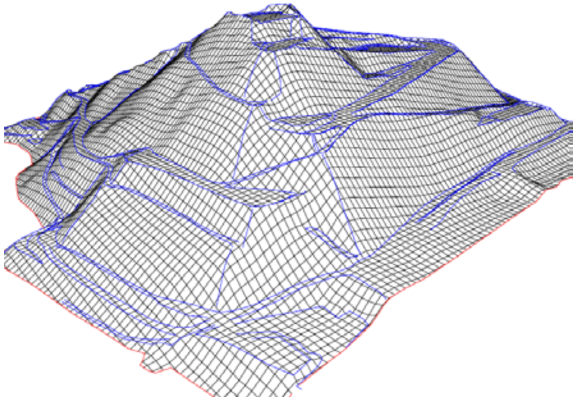
$z = \mathrm{f}(x, y)$

- Piecewise function with only a few parameters
  - Raster: raster heights (per cell), stored as matrix
  - Grid: grid heights (per point), stored as matrix
  - Triangulation: coordinates of individual points + topology of triangles
  - Hybrid: grid + structure lines (e.g. break lines)

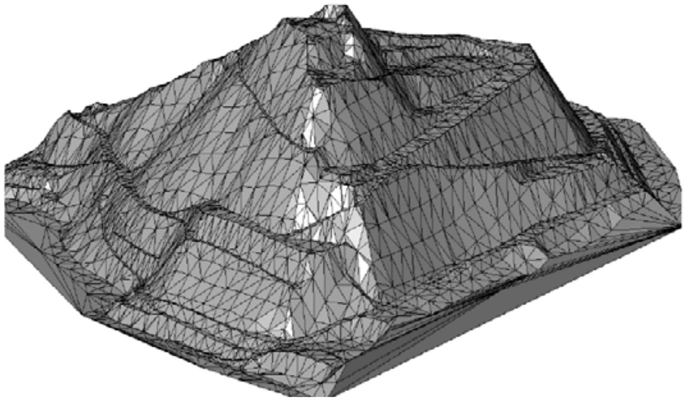
Grid model



Hybrid model

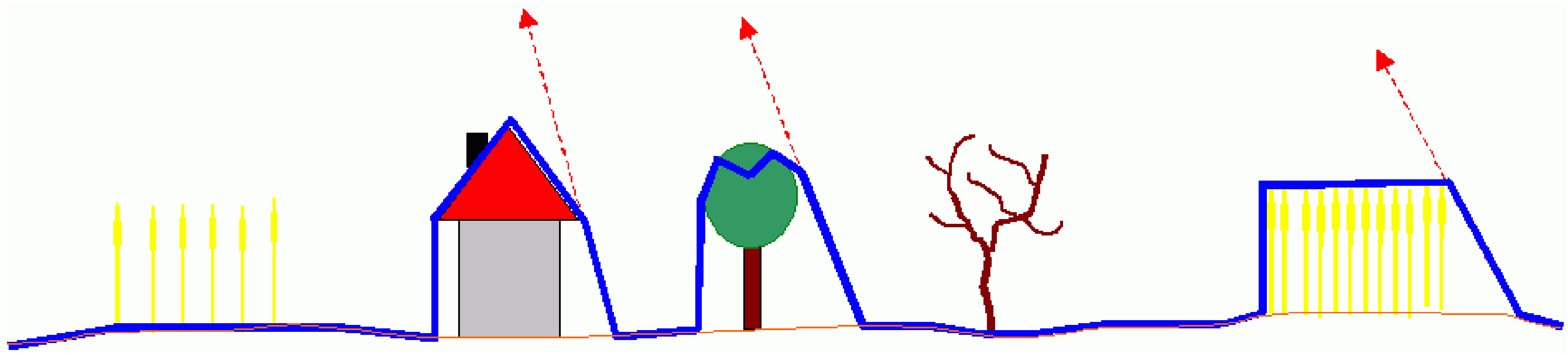


Triangulation

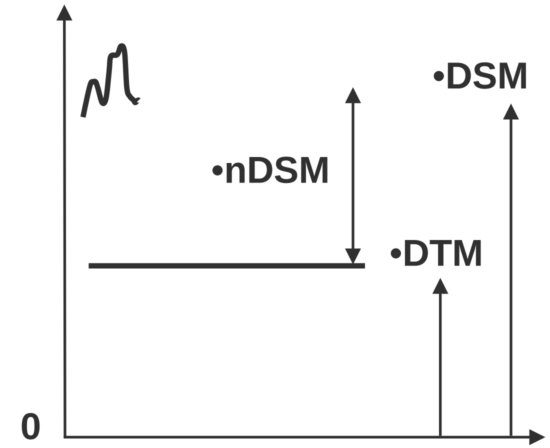


Digital Surface Model - DSM

- **DSM** similar to **DTM**, describing the upper visible surface (w.r.t. bird view)
- Appearance depends on the ground cover and the time of year



- Normalised DSM: nDSM = DSM-DTM



DTM derivation using ALS point clouds

- **ALS point cloud** (combiend from all ALS flight strips)

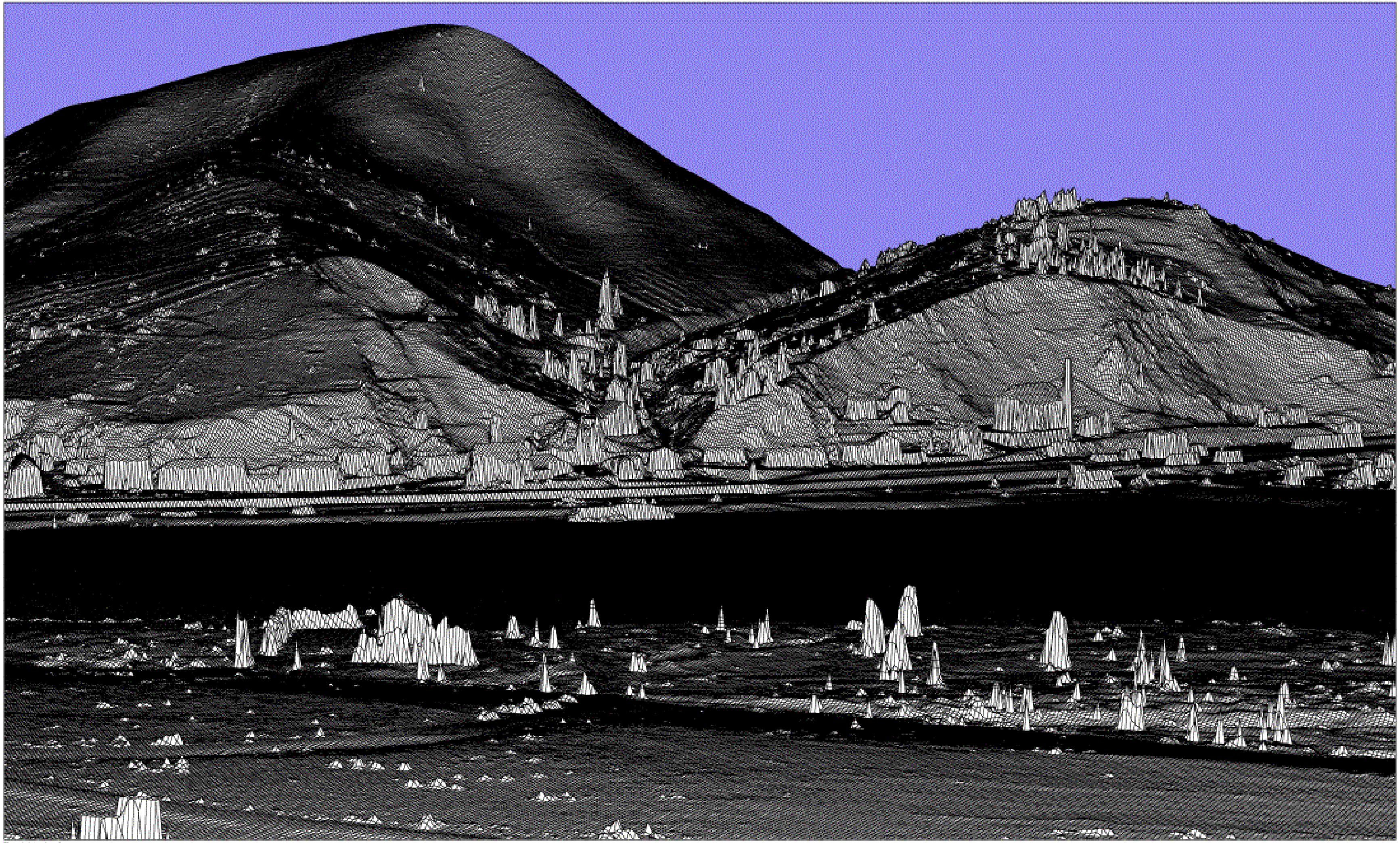
- **Selection of the Last Echo points**

- **Filtering / Classification**

  (Seperation of terrain and off-terrain points; e.g. using robust filtering)

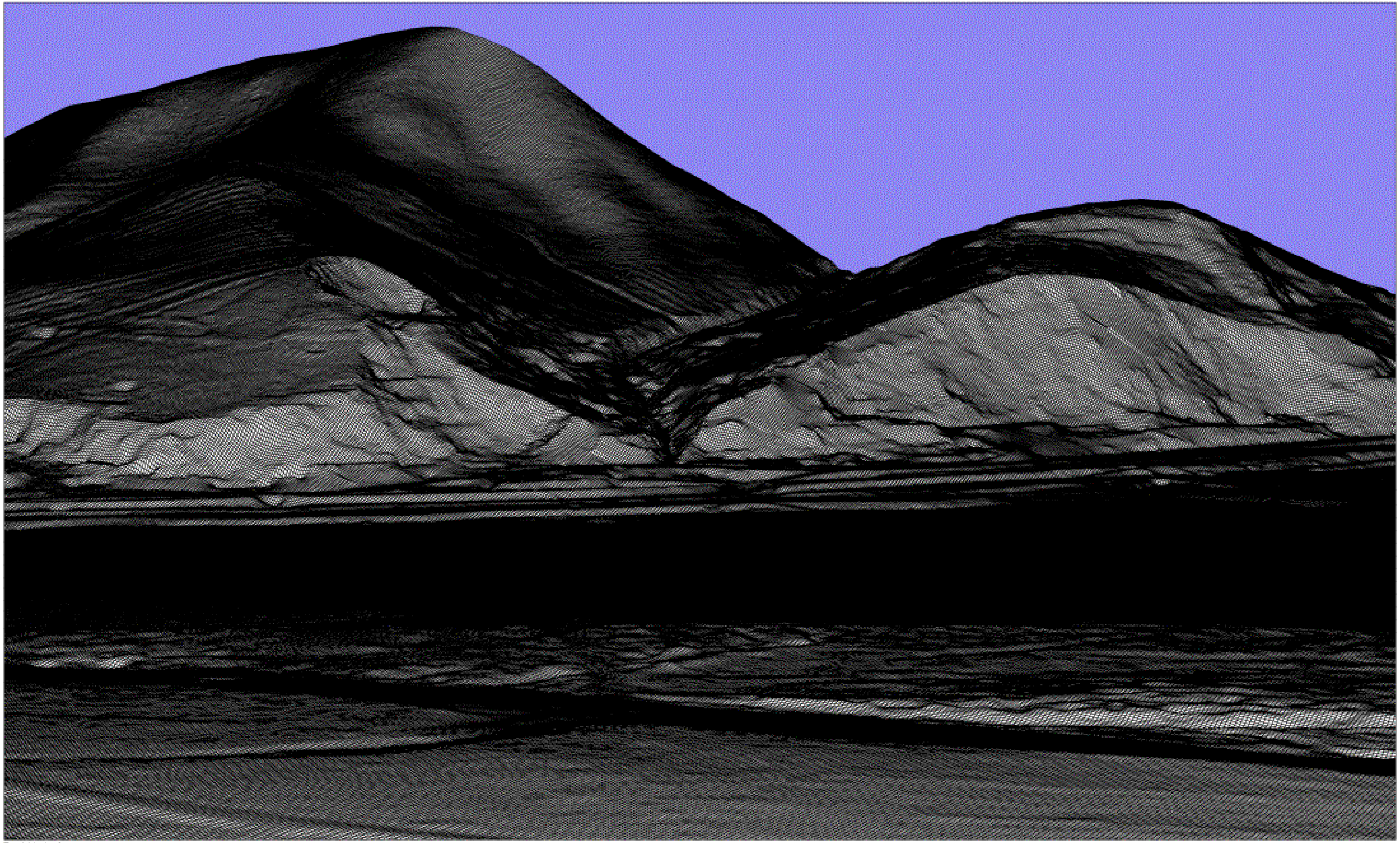
- **Computation of the DTM using all points classified as „terrain“**

From DSM to DTM – example 1



Institut fuer
Photogrammetrie und Fernerkundung
Technische Universitaet Wien

From DSM to DTM – example 1



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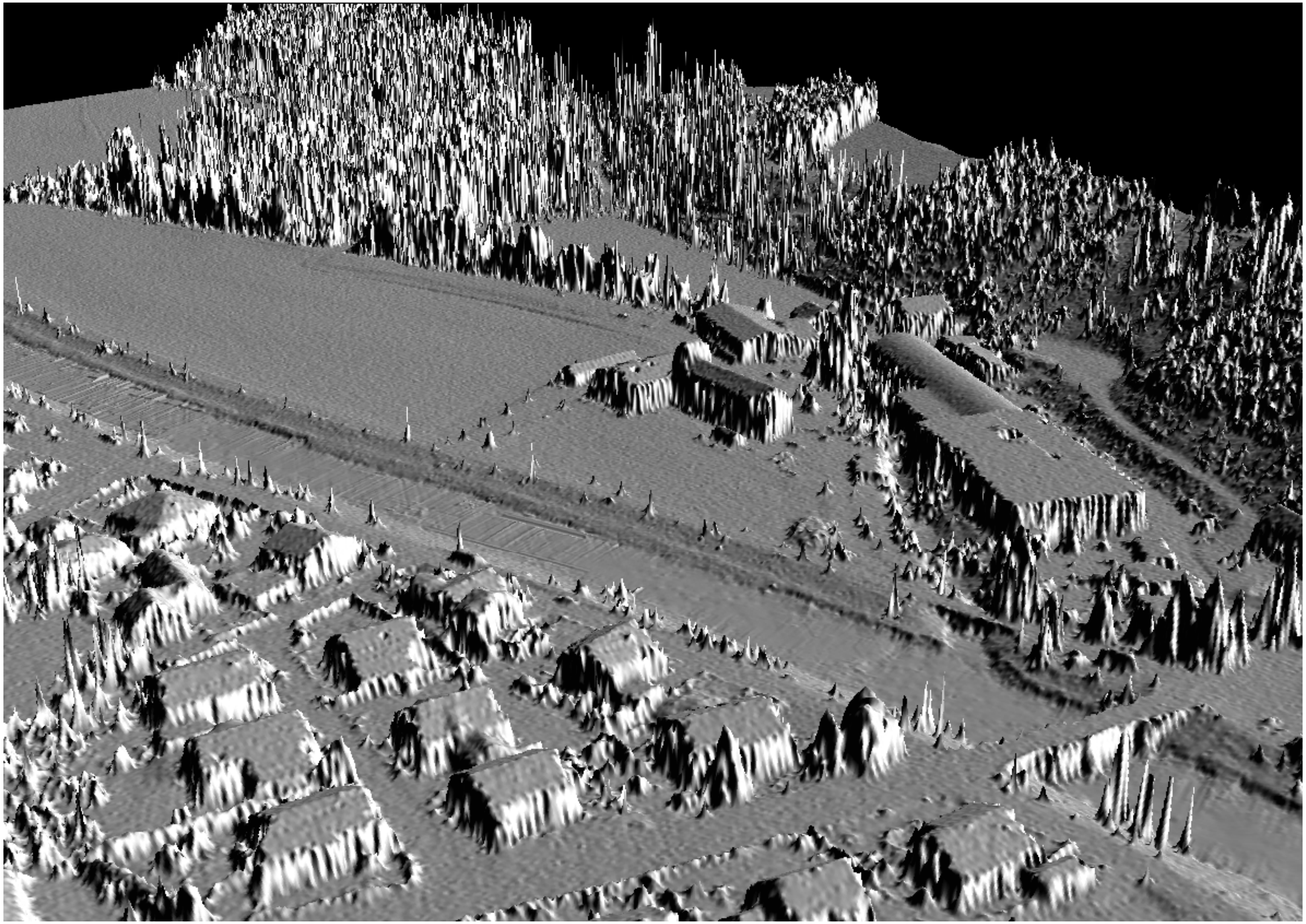
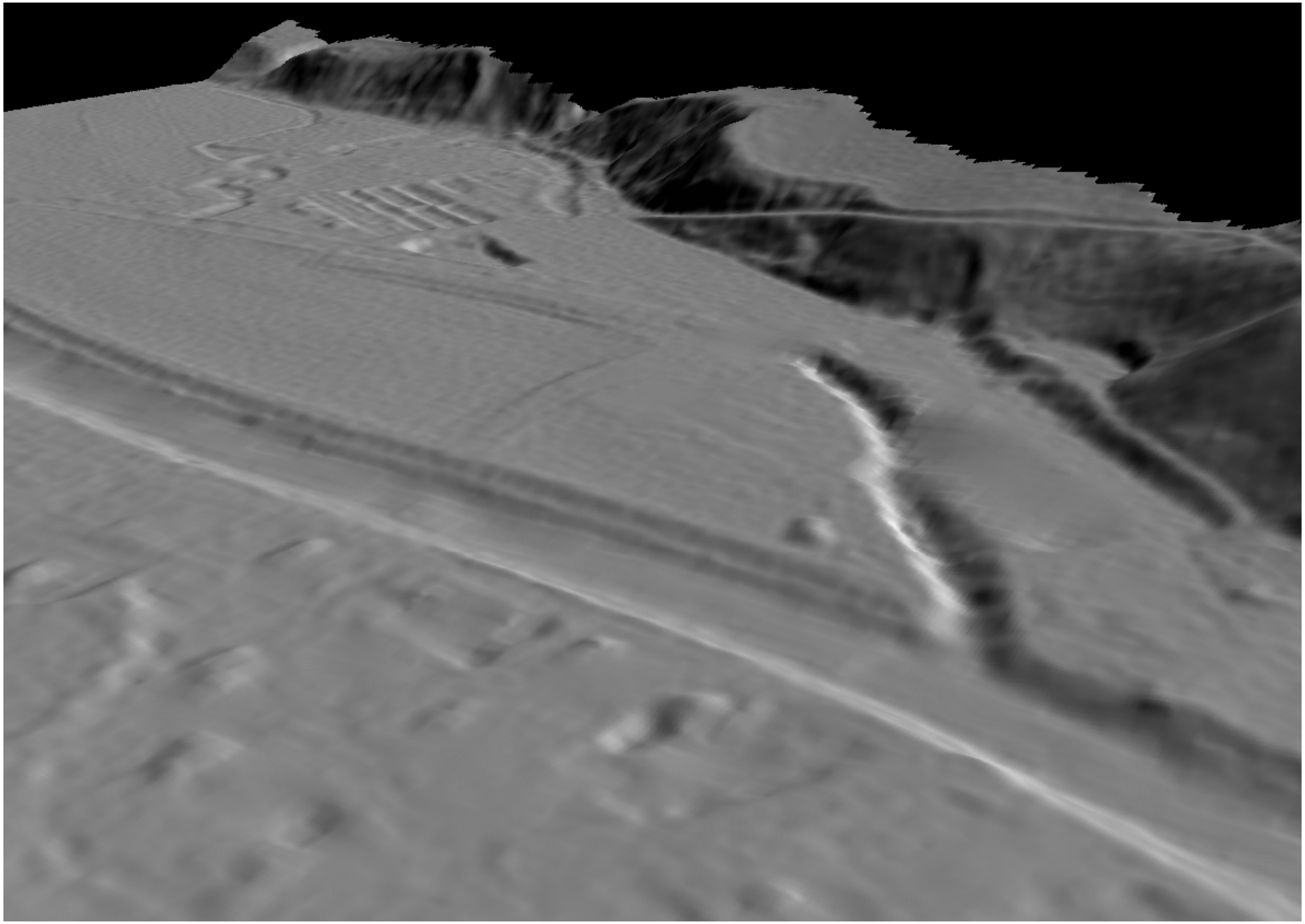
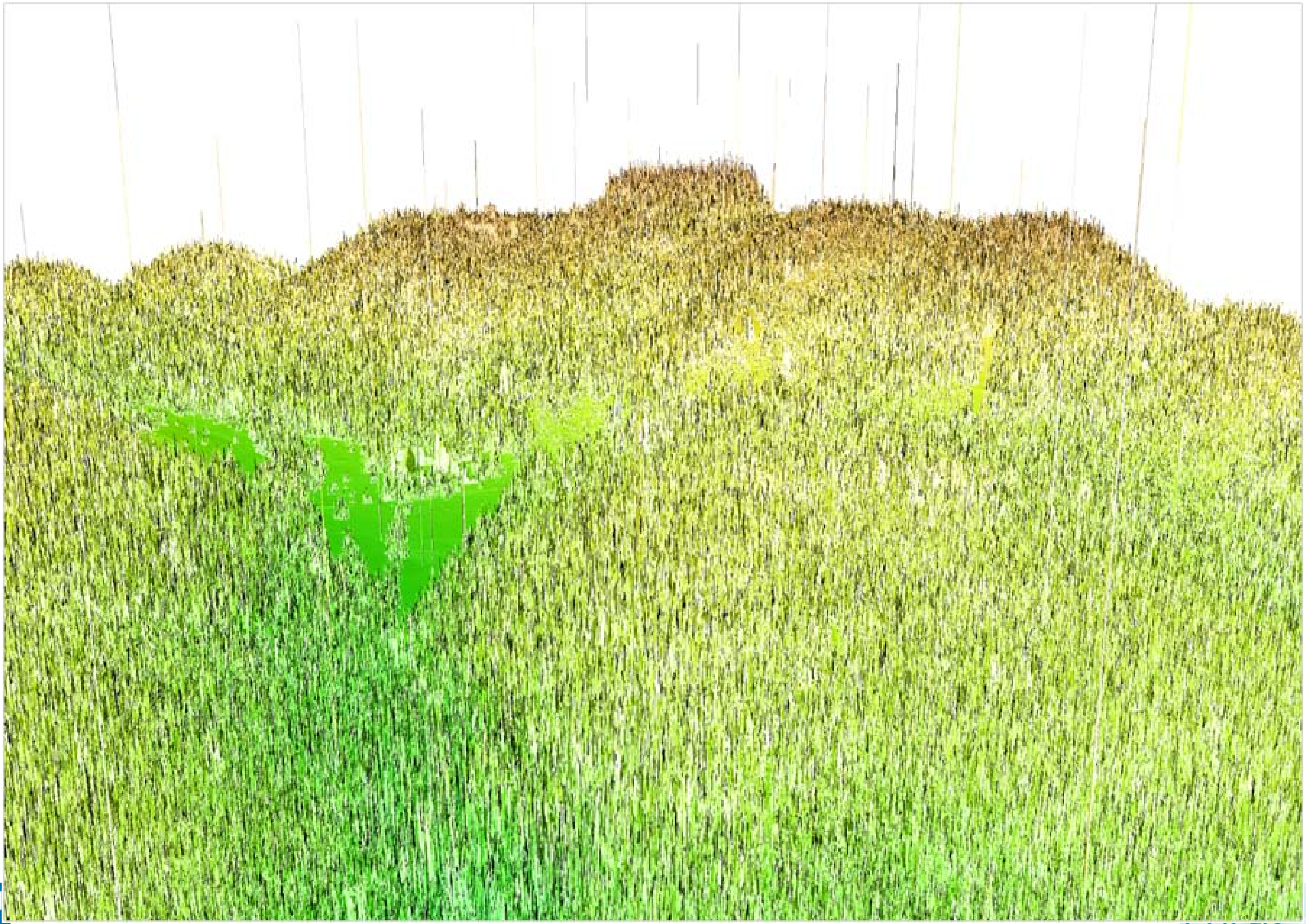
From DSM to DTM – example 2



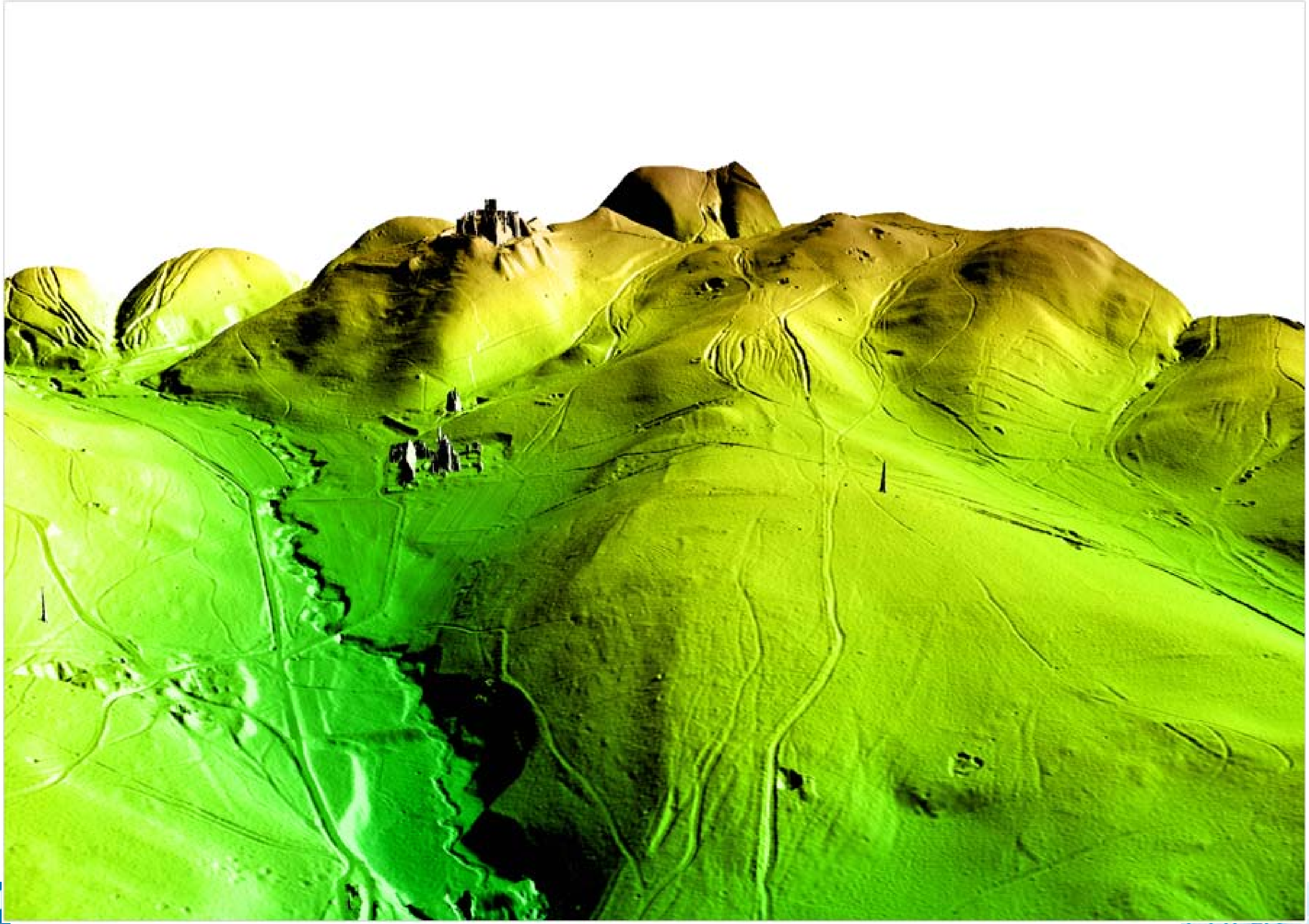
From DSM to DTM – example 2



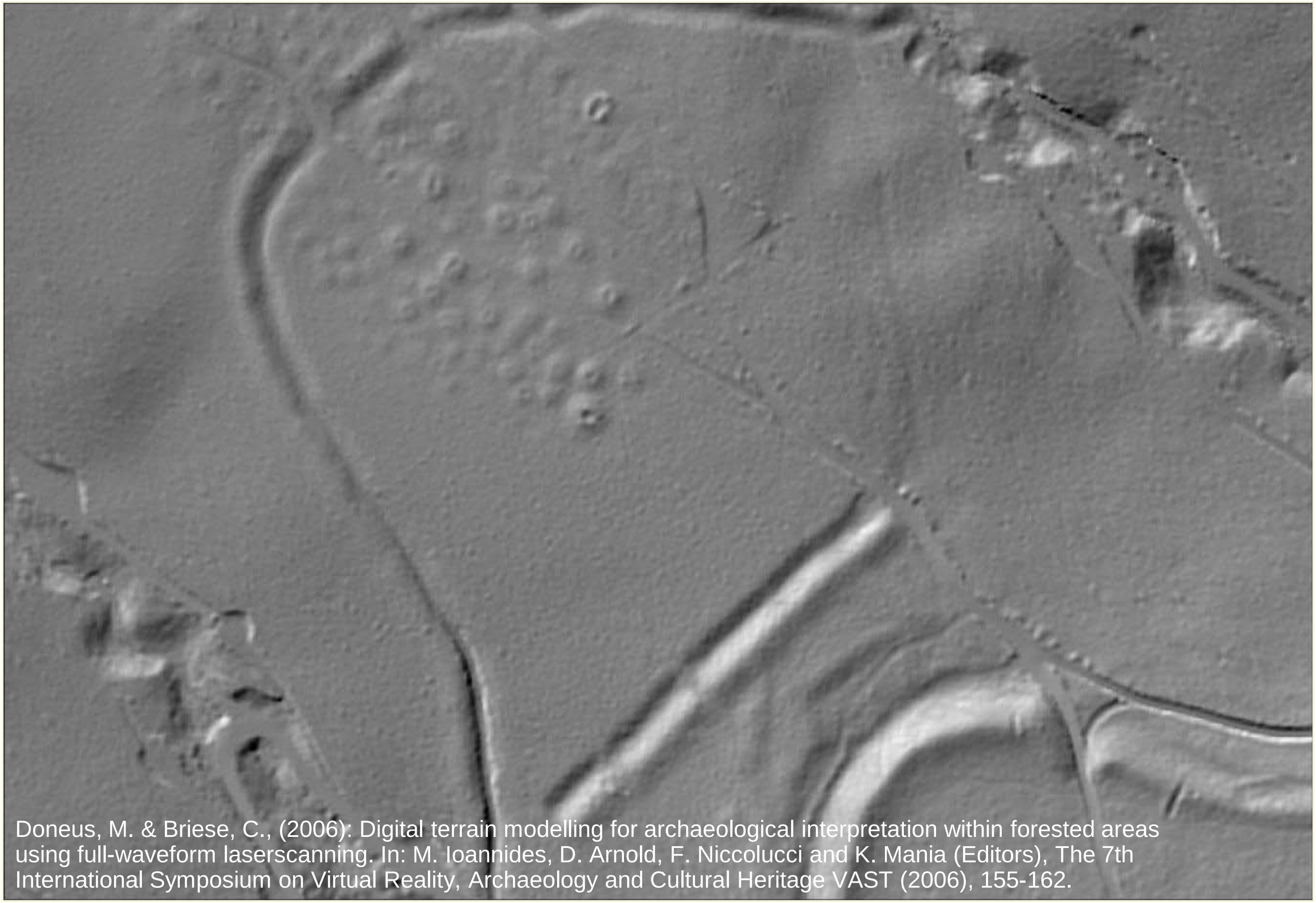
From DSM to DTM – example 3: „St. Anna“



From DSM to DTM – example 3: „St. Anna“



DTM – round barrows – ALS Leithagebirge



Doneus, M. & Briese, C., (2006): Digital terrain modelling for archaeological interpretation within forested areas using full-waveform laserscanning. In: M. Ioannides, D. Arnold, F. Niccolucci and K. Mania (Editors), The 7th International Symposium on Virtual Reality, Archaeology and Cultural Heritage VAST (2006), 155-162.

Summary

- Part I - LIDAR principle
  - LIDAR principle
  - Laser Scanning - Laser beam deflection
  - Current Systems
    - Discrete Return ALS
    - Full-waveform ALS
  - Recent Developments
    - Full-waveform ALS
    - Multiple pulses in air
- Part II - Principle of Georeferencing
  - Direct Georeferencing
  - Strip Adjustment
- Part III
  - Examples: Point Clouds
  - Surface and Terrain Models