TECHNISCHE UNIVERSITÄT DRESDEN

Faculty of Environmental Science Institute of Photogrammetry and Remote Sensing

Analysis and Modeling of the Effect of Wave Patterns on Refraction in Airborne LiDAR Bathymetry

P. Westfeld, K. Richter and H.-G. Maas

Rostock, 11/15/2016

ALB – Principle

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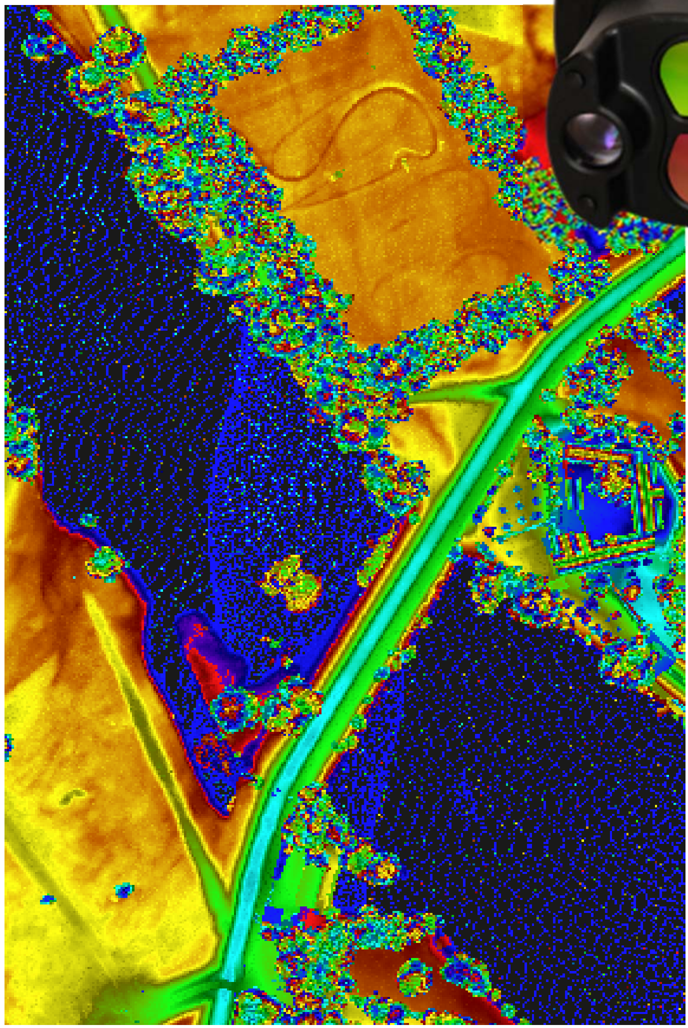

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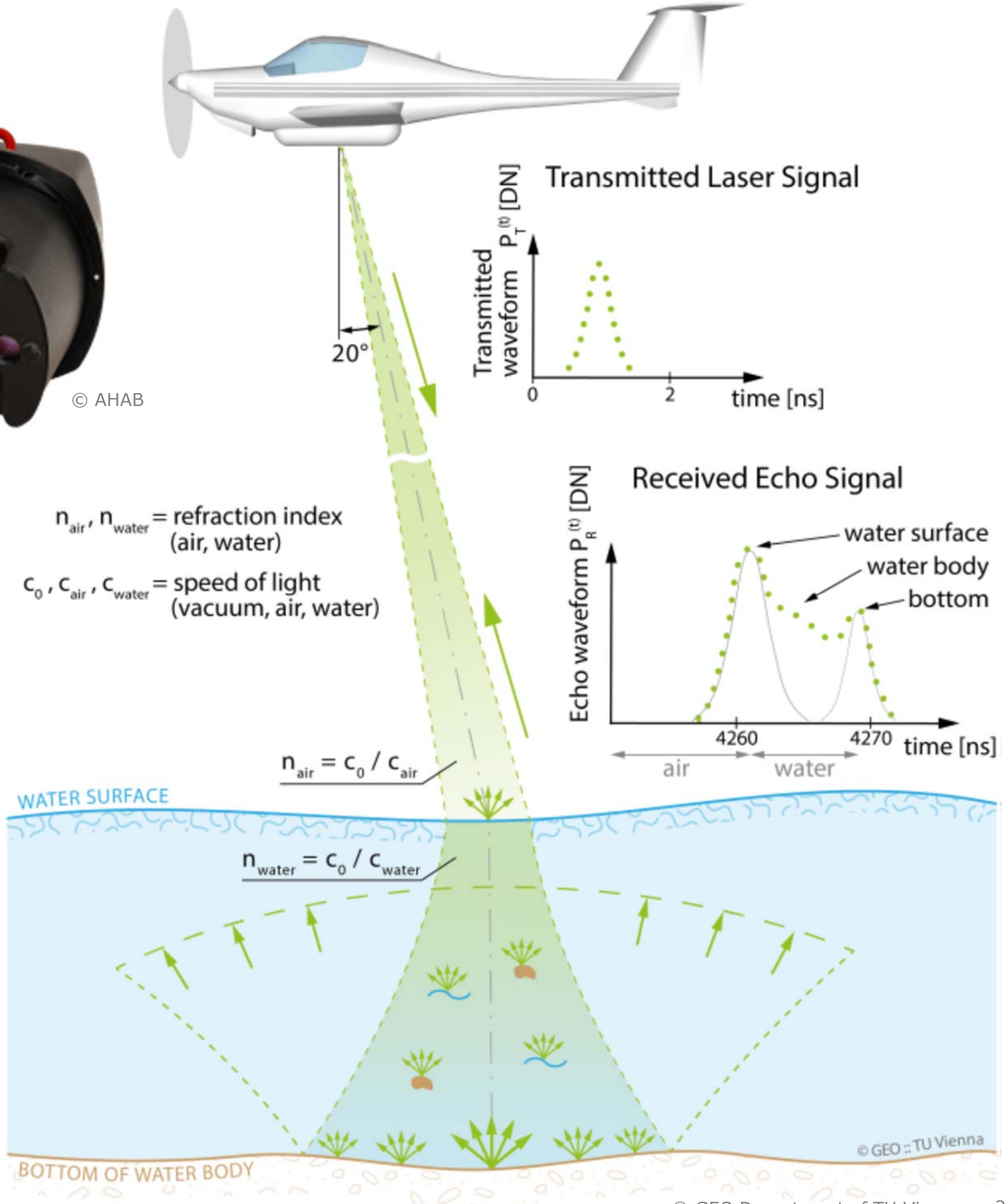
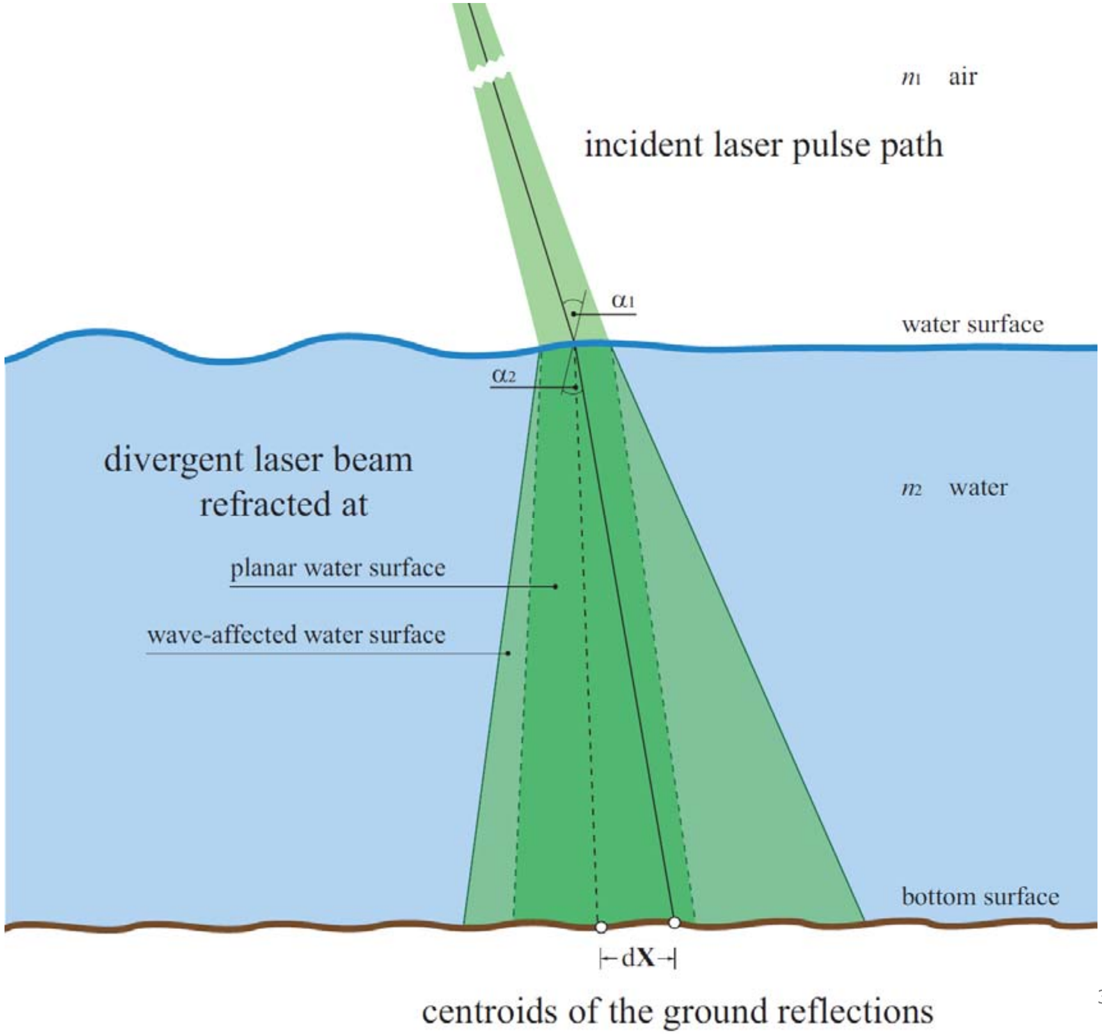


Local wave-induced water surface inclination lead to geometric displacement

- **Lateral displacement d*XY*** (caused by errors in the local refraction angle) propagates as **depth error d*Z*** (expressed as changes in ray path lengths)

River waves

Ocean waves



Aim of the work

- **Investigate the effect of waves** on the refraction affecting the path of the laser pulse under water
- Simulation of typical wave patterns (river, ocean)
- Analysis of the **impact on the 3D coordinates** at the bottom of the water body

A Introduction

B Methodology

C Results

D Conclusion and outlook

Two different levels of complexity in water surface modelling

Simple symmetrical waves

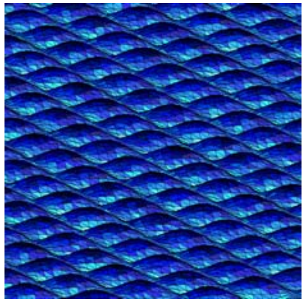
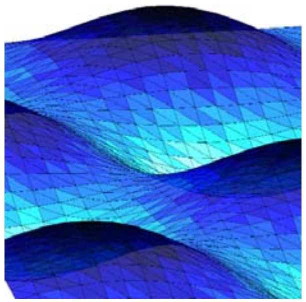
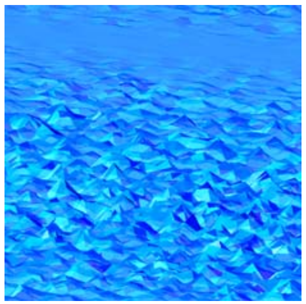
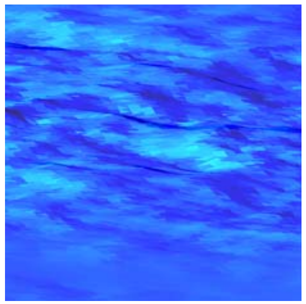
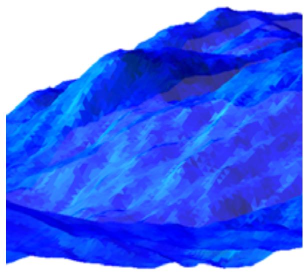
- Periodic sine and cosine functions
- Amplitude and frequency specify **height**, **width** and **slope** of a single wave

Complex wave structures

- Horizontally and vertically running waves
- Adapting algorithm for simulating ocean water from **Jerry Tessendorf (2001)**

    1. *Define regular grid of 2D points*
    2. *Calculate set of ‚random‘ amplitudes (based on oceanographic conditions)*
    3. *Use FFT on amplitudes to obtain grid‘s wave heights*

- Simplified parameterization: **wind speed, wind direction, length of biggest wave**

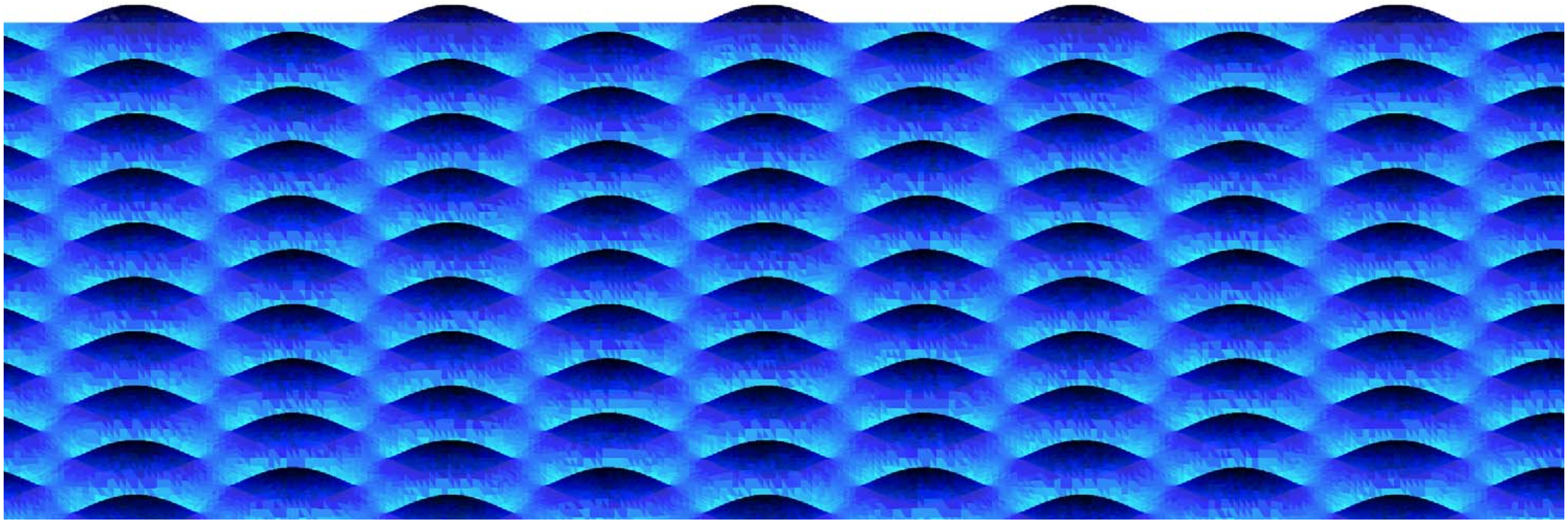







Water surface modelling

Periodic wave patterns (Σ1)

Calm, rippled sea state
with slight, high frequency waves.

37cm	Width
±10cm	Height
<30°	Slope

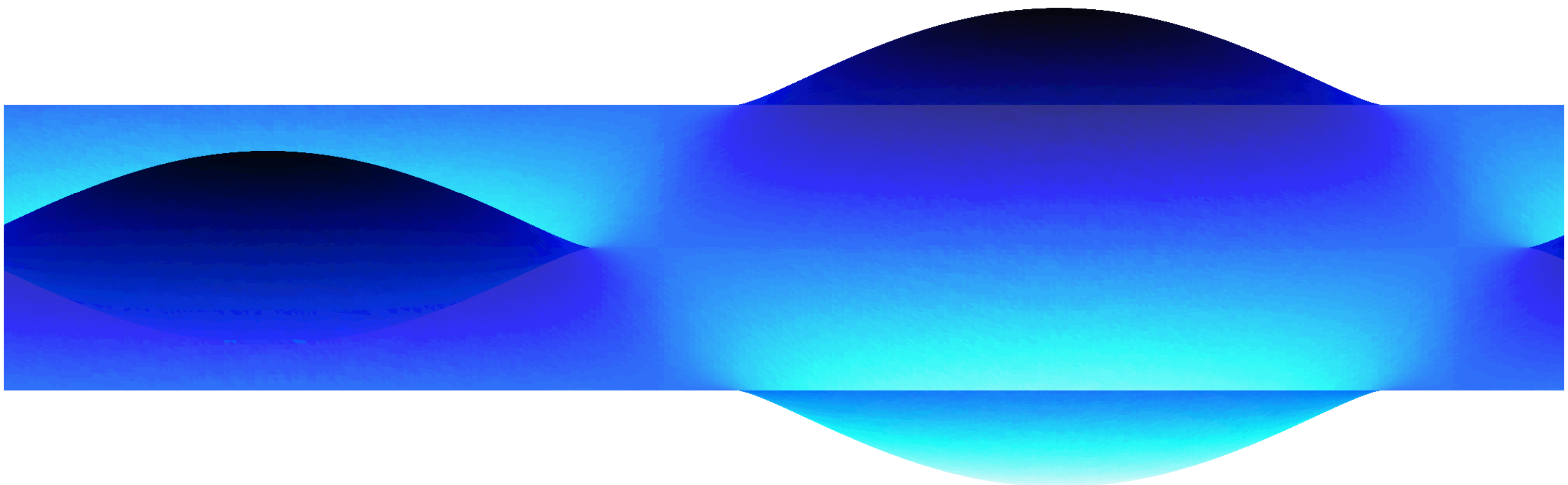


Water surface modelling

Periodic wave patterns (Σ2)

Moderate ocean sea state with long waves.

4m	Width
±1m	Height
<25°	Slope



Water surface modelling

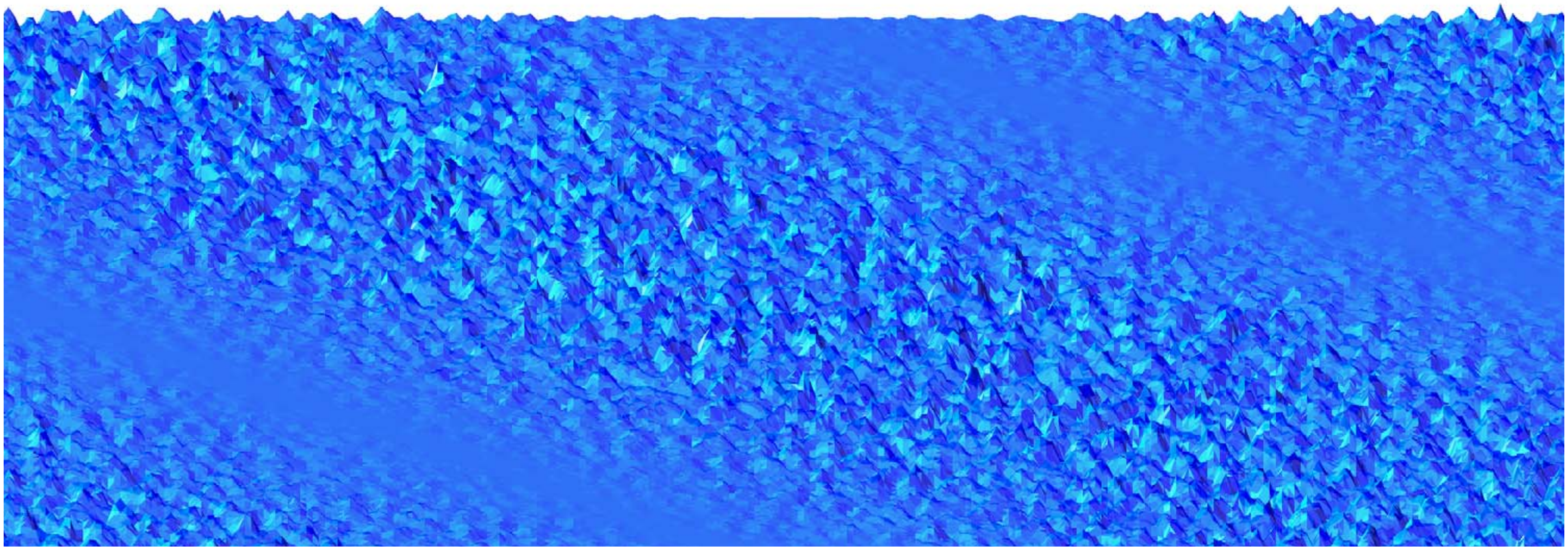
Complex wave patterns (Y1)

10cm Width

±5cm Height

<50° Slope

Calm, rippled sea state
with short but steep waves.

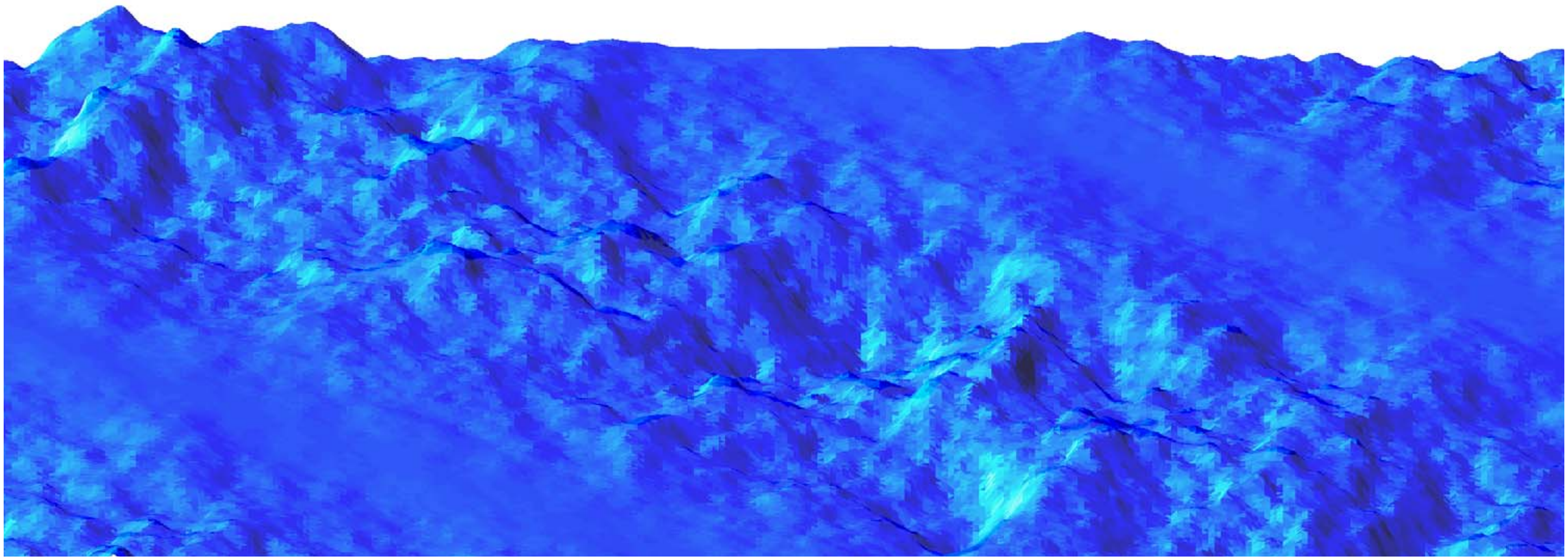


Water surface modelling

Complex wave patterns (Y2)

Smooth, shallow wavelets with small crests and troughs.

50cm	Width
±15cm	Height
<25°	Slope

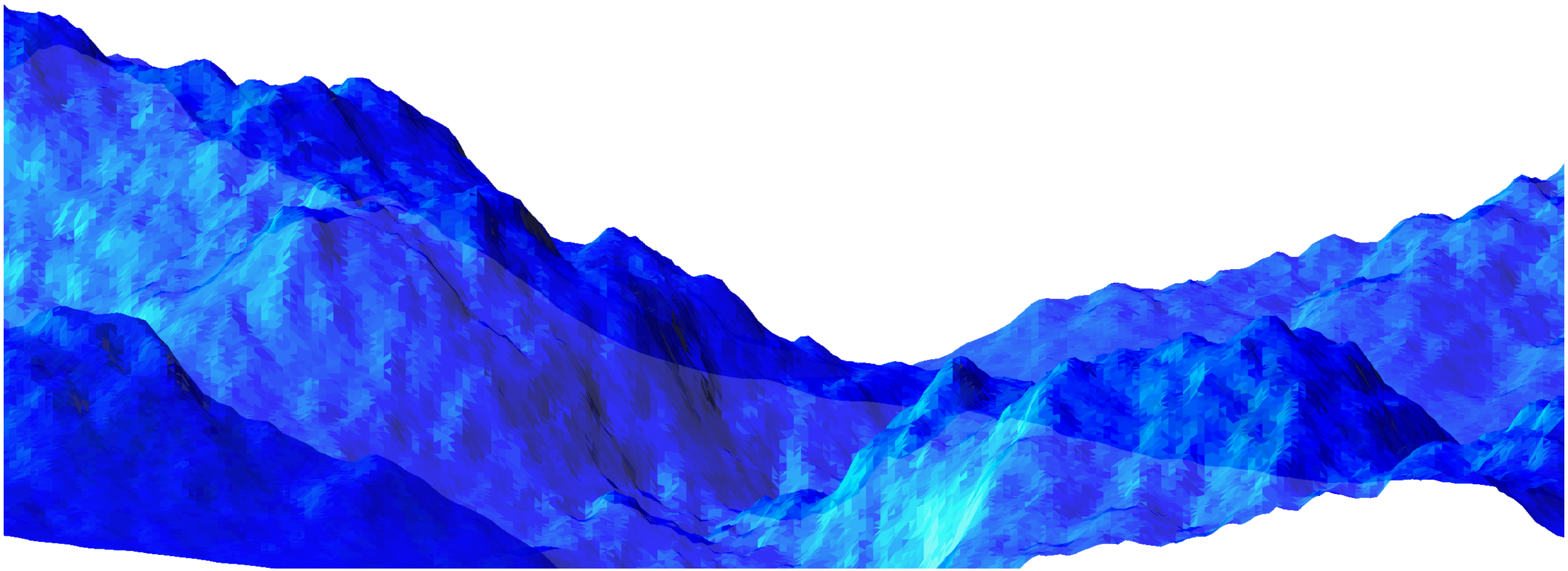


Water surface modelling

Complex wave patterns (Y3)

Ocean sea state with
moderate wave heights and long sea swell.

- **6m** — Width
- **±1.5m** — Height
- **<45°** — Slope

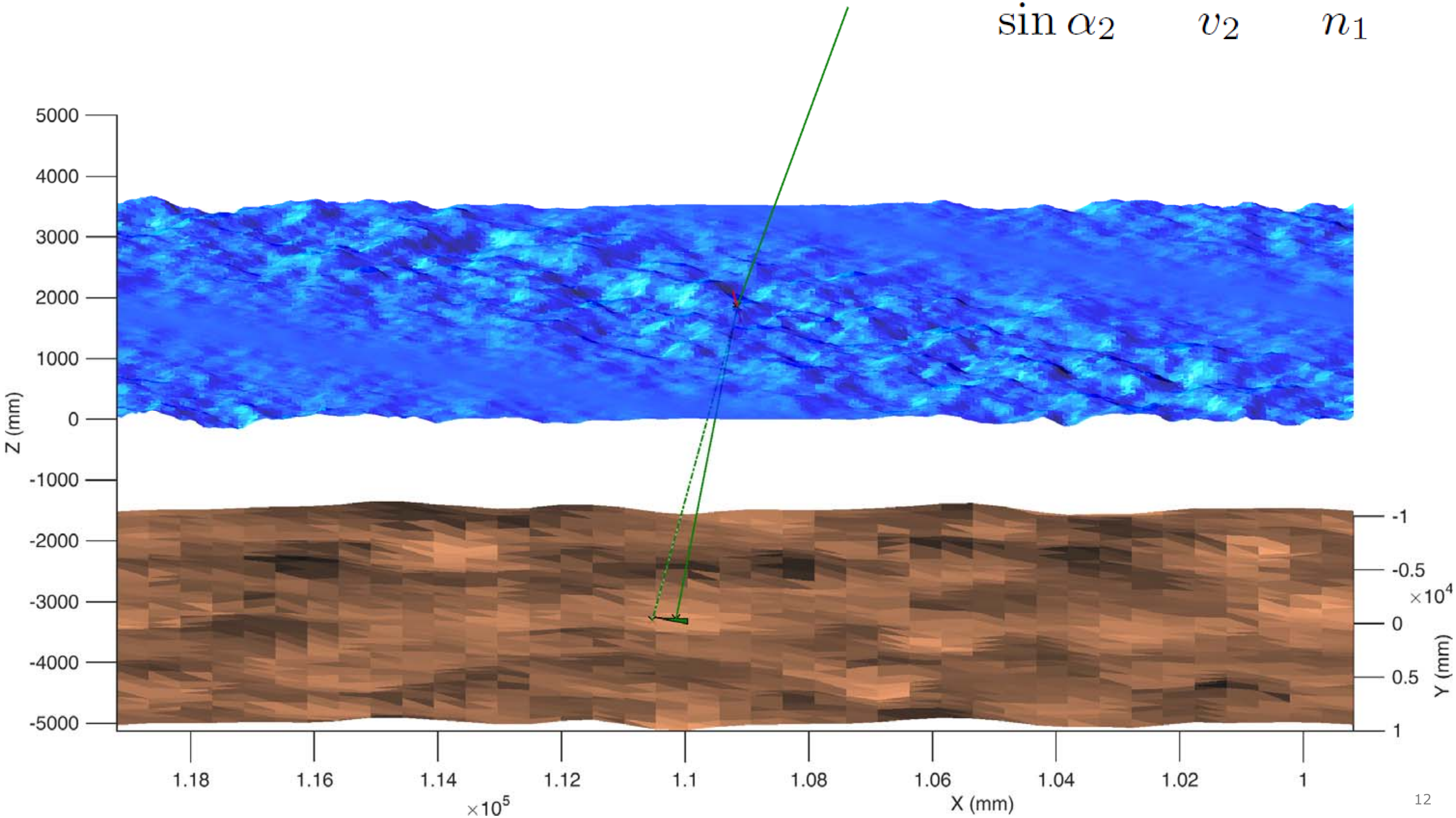


Ray path modelling

Infinitesimal small line

Snell's law

$$\frac{\sin \alpha_1}{\sin \alpha_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1}$$

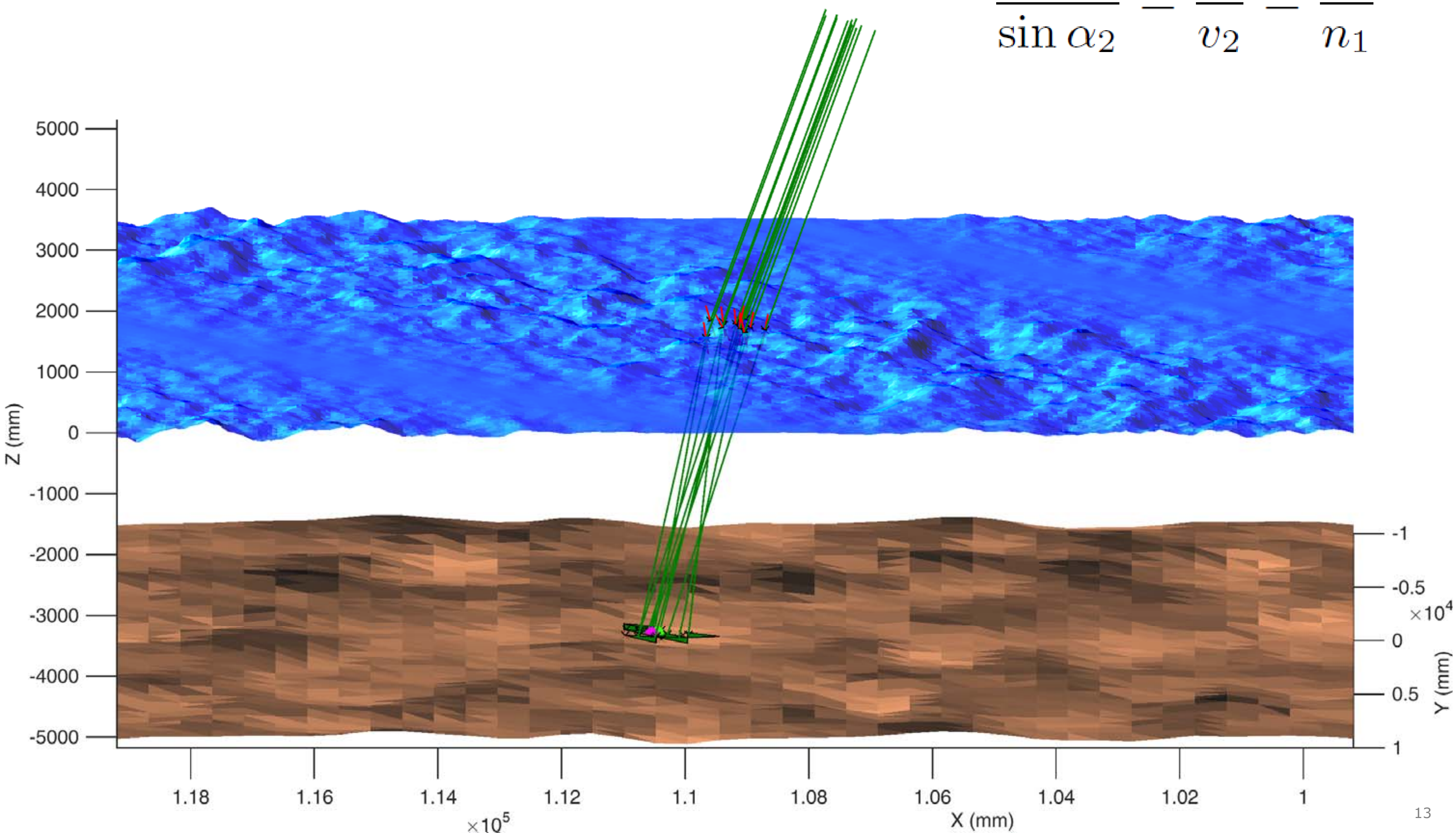


Ray path modelling

Finite laser pulse cross section

Snell‘s law

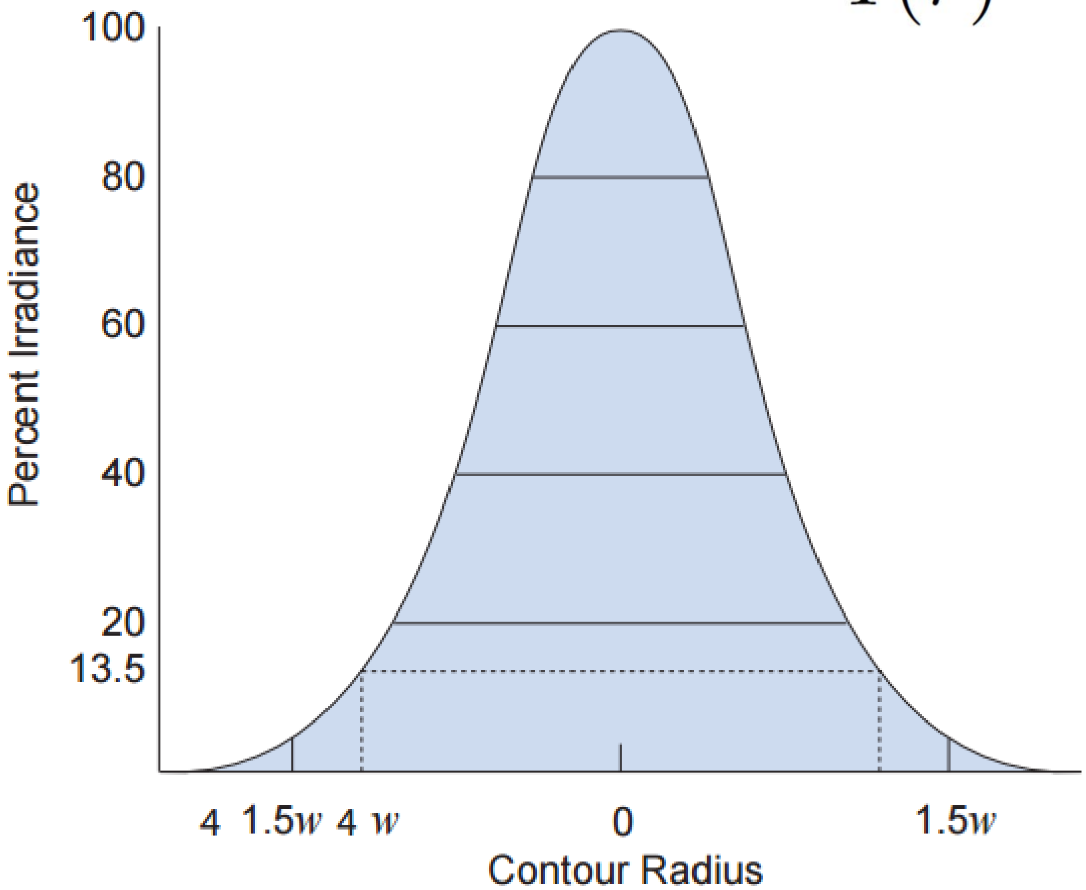
$$\frac{\sin \alpha_1}{\sin \alpha_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1}$$

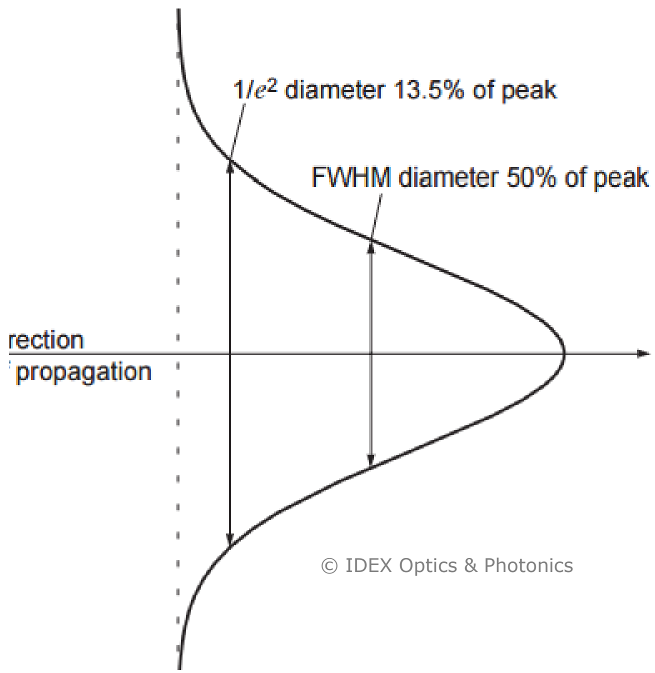


Ray path modelling

The intensity distribution within the incident laser pulse should follow a Gaussian intensity profile.

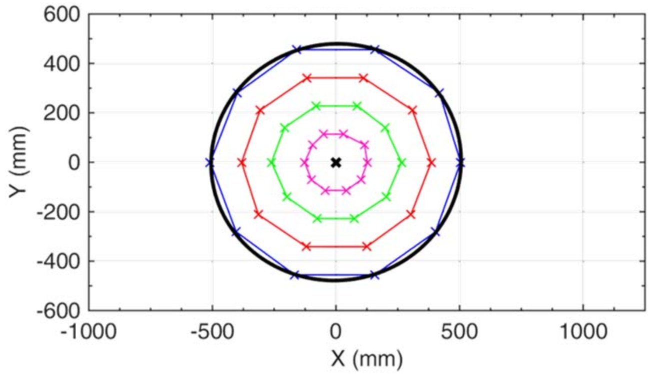
$$I(r) = I_0 \cdot e^{2r^2/r_{\max}^2}$$

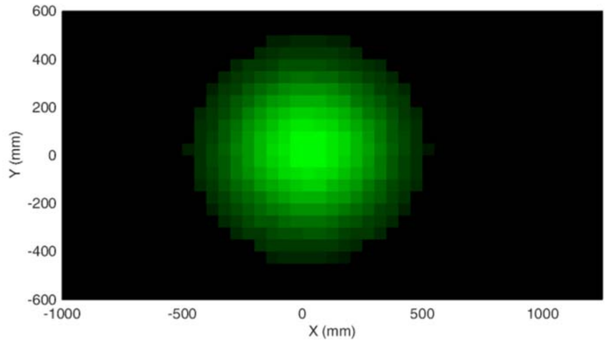


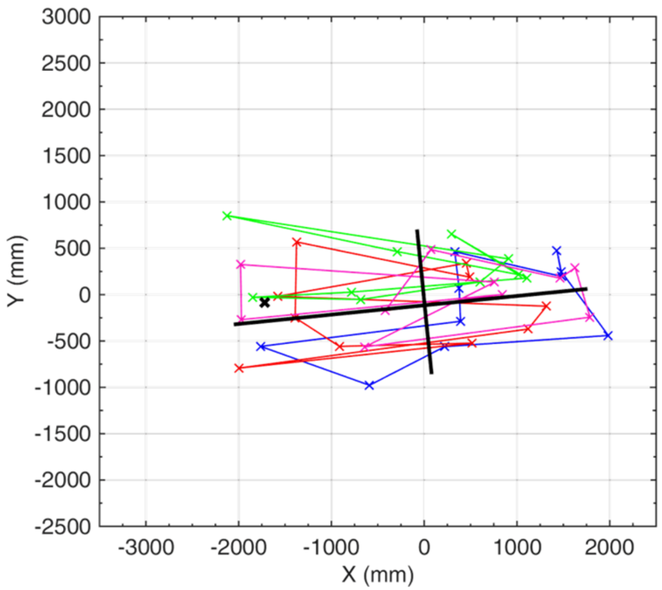


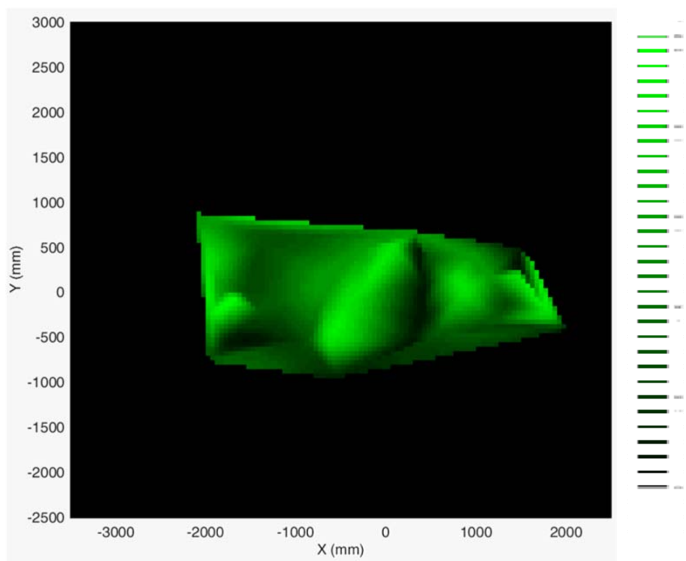
Ray path modelling

Ground reflections are represented by centroid coordinates, weighted accordingly to the intensity distribution.









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Parameters of the flight campaign simulated

Airborne survey campaign (Weiß, DGPF 24/2015), Leica AHAB Chiroptera$_{\mathrm{I}}$ LiDAR

- **Aircraft altitude** is **300m**
- **Beam divergence** of **3mrad** → **1m laser footprints** at water surface
- **Beam deflection** in elliptical scanning pattern is **20deg**

- 5 different water surface topographies (grid size: 20mm × 20mm)
- Smooth, continuous bottom surface (grid size: 80mm × 80mm)

3D coordinate displacement

Systematic Approach

Local planar water surface elements vs.

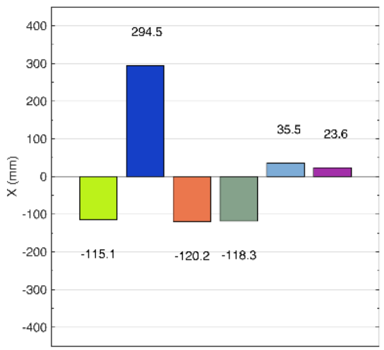
(≙ common assumption made in ALB applications)

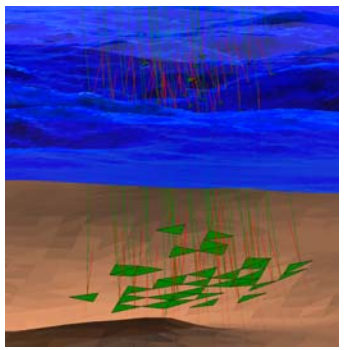
non-planar, wavy water surface

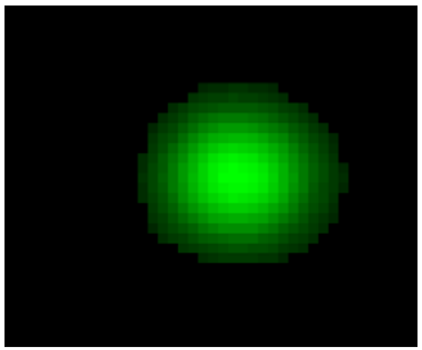
(≙ consideration of local wave-induced inclination)

- **Lateral displacement d*XY*** is calculated from differences between the irradiance-weighted centroids of the ground reflections
- Changes in underwater ray path lengths express the **depth error d*Z***

- 100 consecutive epochs
- 50 infinitesimal paths representing one finite cross section
- Simple periodic vs. complex realistic modelling





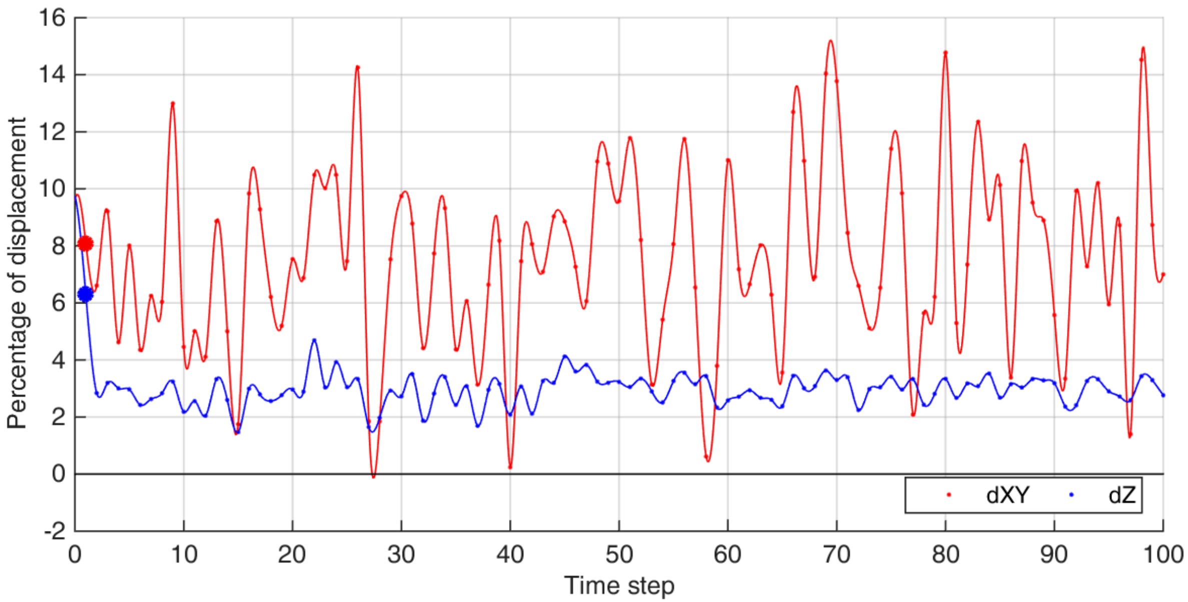


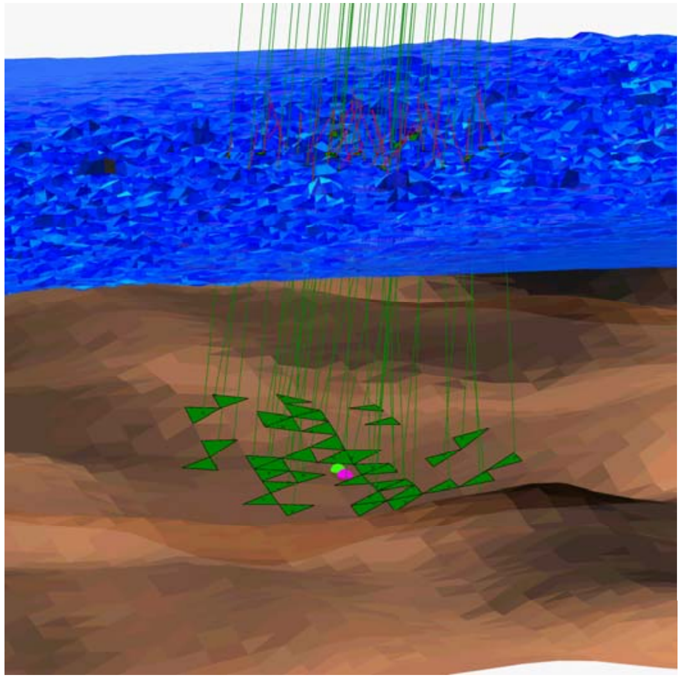
3D coordinate displacement

Calm, rippled sea with short but steep waves (Y1)

- Significant effects occur, even if **multiple wave cycles** are within the laser footprint

	RMSE (% / @5m)	
d*XY*	7.5% (max. 14.8%)	375 mm (max. 740 mm)
d*Z*	3.0% (max. 6.3%)	150 mm (max. 315 mm)



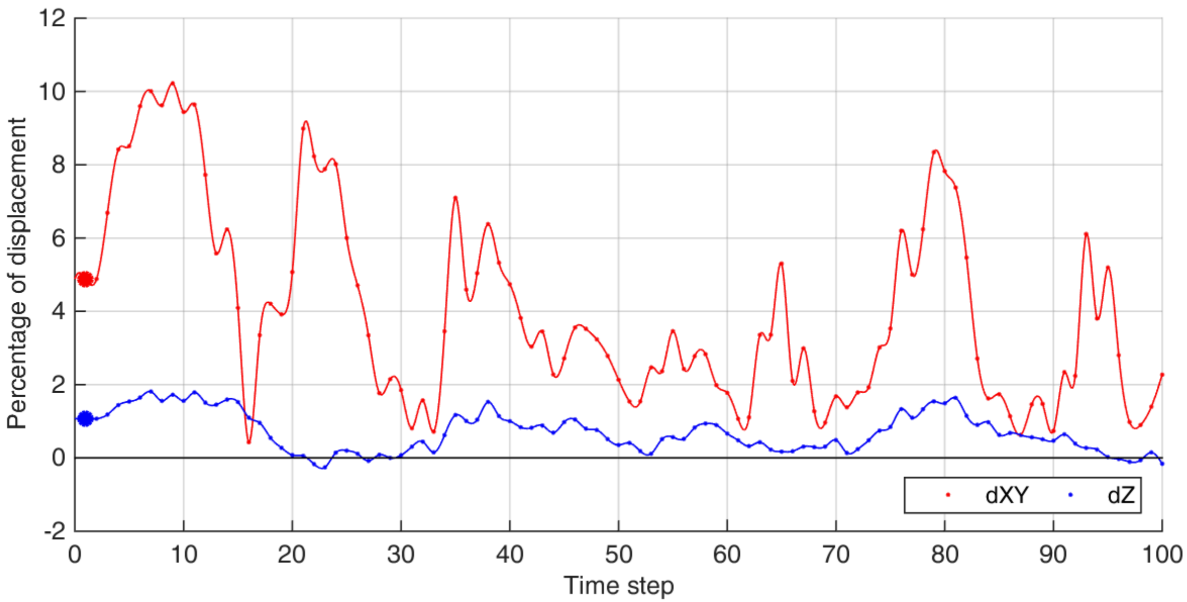


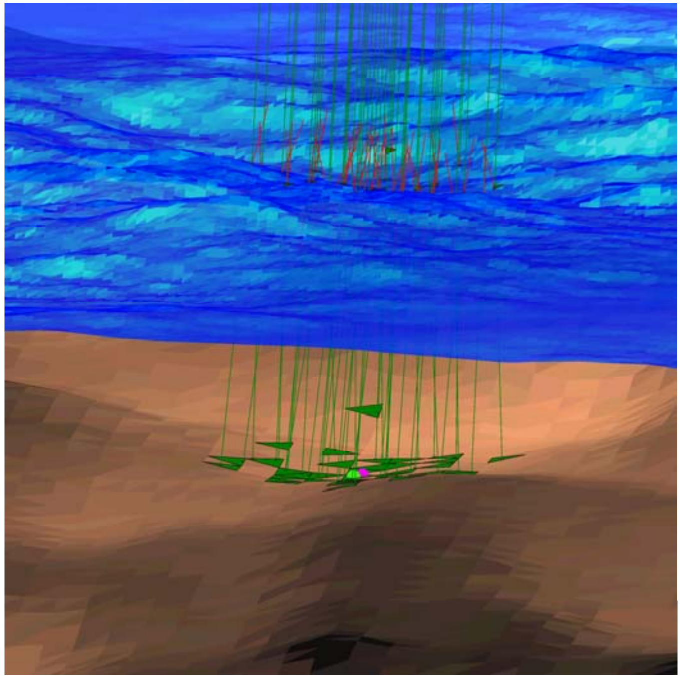
3D coordinate displacement

Smooth, shallow wavelets with small crests and troughs (Y2)

- Significant effects occur, even if **multiple wave cycles** are within the laser footprint

	RMSE (% / @5m)	
d*XY*	4.0% (max. 10.2%)	200 mm (max. 510 mm)
d*Z*	0.9% (max. 1.8%)	35 mm (max. 90 mm)



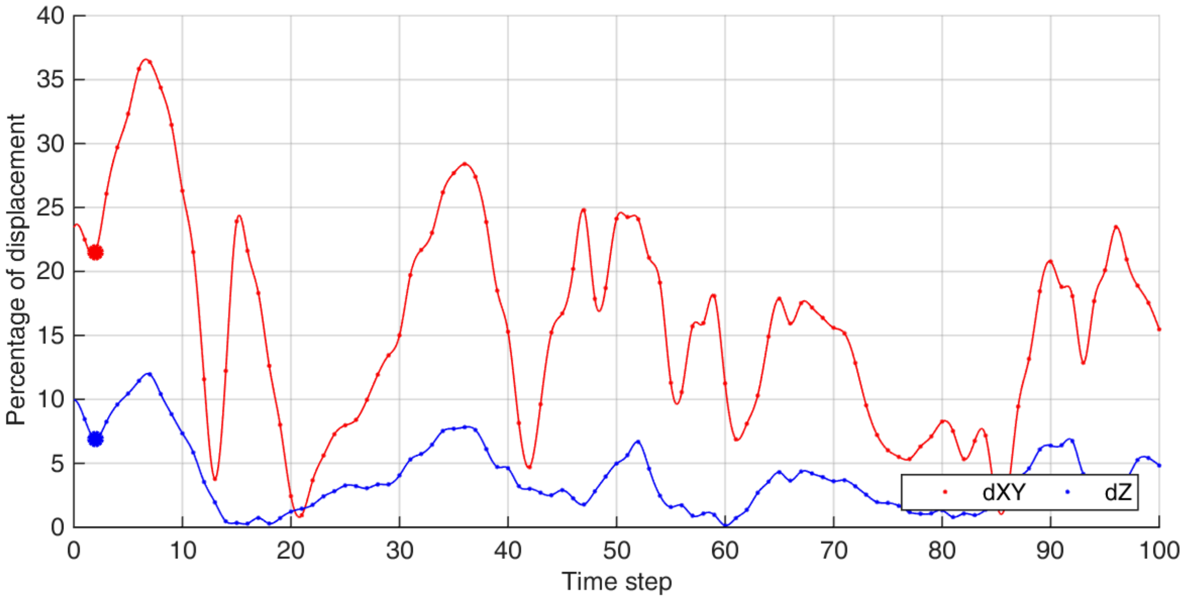


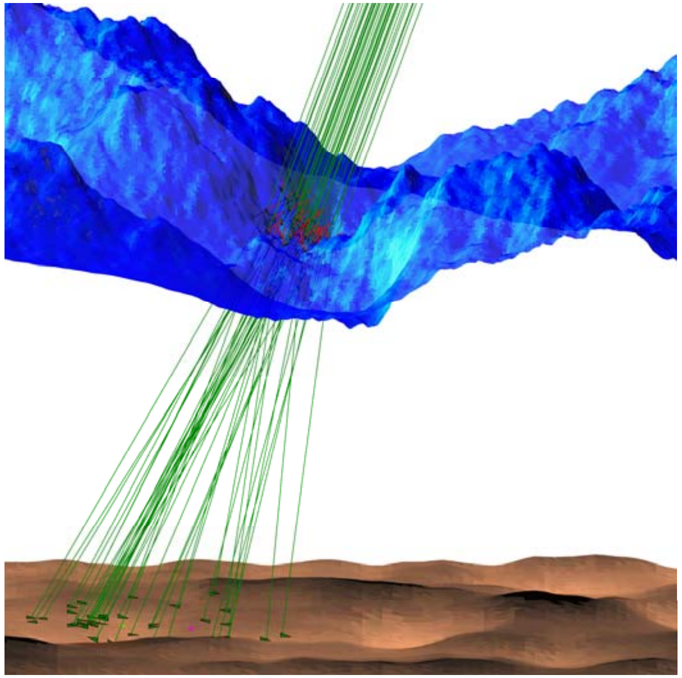
3D coordinate displacement

Moderate, long ocean waves (Y3)

- Shifting effects are more distinct if the **period length is greater than the footprint**

	RMSE (% / @5m)	
d*XY*	15.8% (max. 36.4%)	790 mm (max. 1820 mm)
d*Z*	4.7% (max. 12.0%)	235 mm (max. 600 mm)





3D coordinate displacement

Summary

- Lateral bottom point displacement can take on **significant dimensions**
- Underwater laser ray path becomes longer → **water body bottom model too deep**

- **Improvements in 3D object coordinate determination** after modeling simple symmetrical waves
- More complex, asymmetric-wave models **increase improvements by a factor 2**

Wave pattern	dXY (%)			dZ (%)		
	min. / max. / **RMSE**					
Σ_1	2.7	5.0	**4.0**	-1.0	1.2	**0.7**
Σ_2	5.7	14.5	**11.1**	-1.5	4.3	**2.6**
Υ_1	0.2	14.8	**7.5**	1.5	6.3	**3.0**
Υ_2	0.4	10.2	**4.0**	-0.2	1.8	**0.9**
Υ_3	0.9	36.4	**15.8**	0.1	12.0	**4.7**

Changes in laser footprint size and shape

Elliptical footprint at water surface

- Size depends on flying height and beam divergence
- Sea state induces slight deformation
- Analyze **length of major and minor axis**

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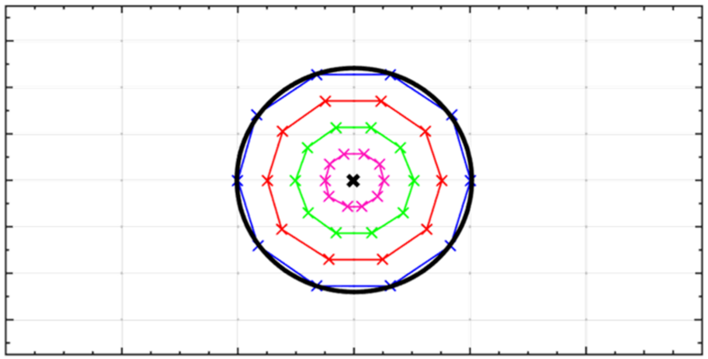
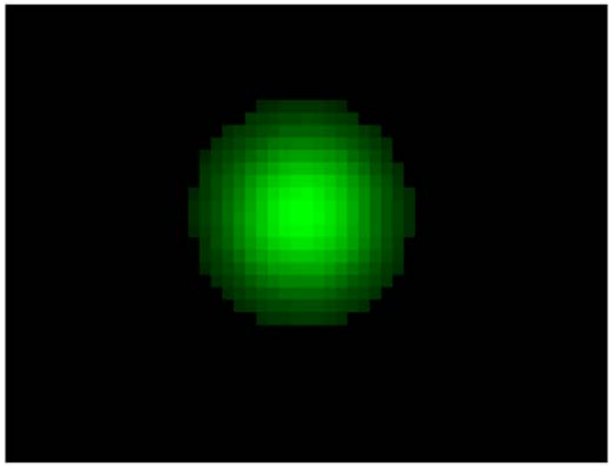




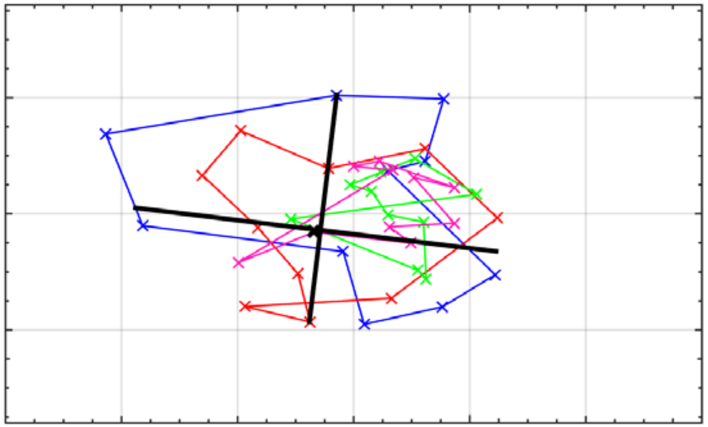
Changes in laser footprint size and shape

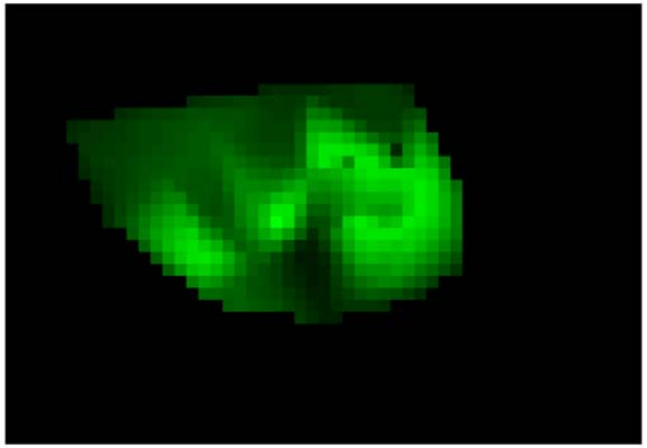
Elliptical footprint at water surface

- Size depends on flying height and beam divergence
- Sea state induces slight deformation
- Analyze **length of major and minor axis**

Blurred footprint at water bottom

- Discrete laser points are misaligned (beam expansion, beam focusing)
- Intensity distribution no longer follows a Gaussian distribution
- Compute **length of 1st and 2nd principal component**

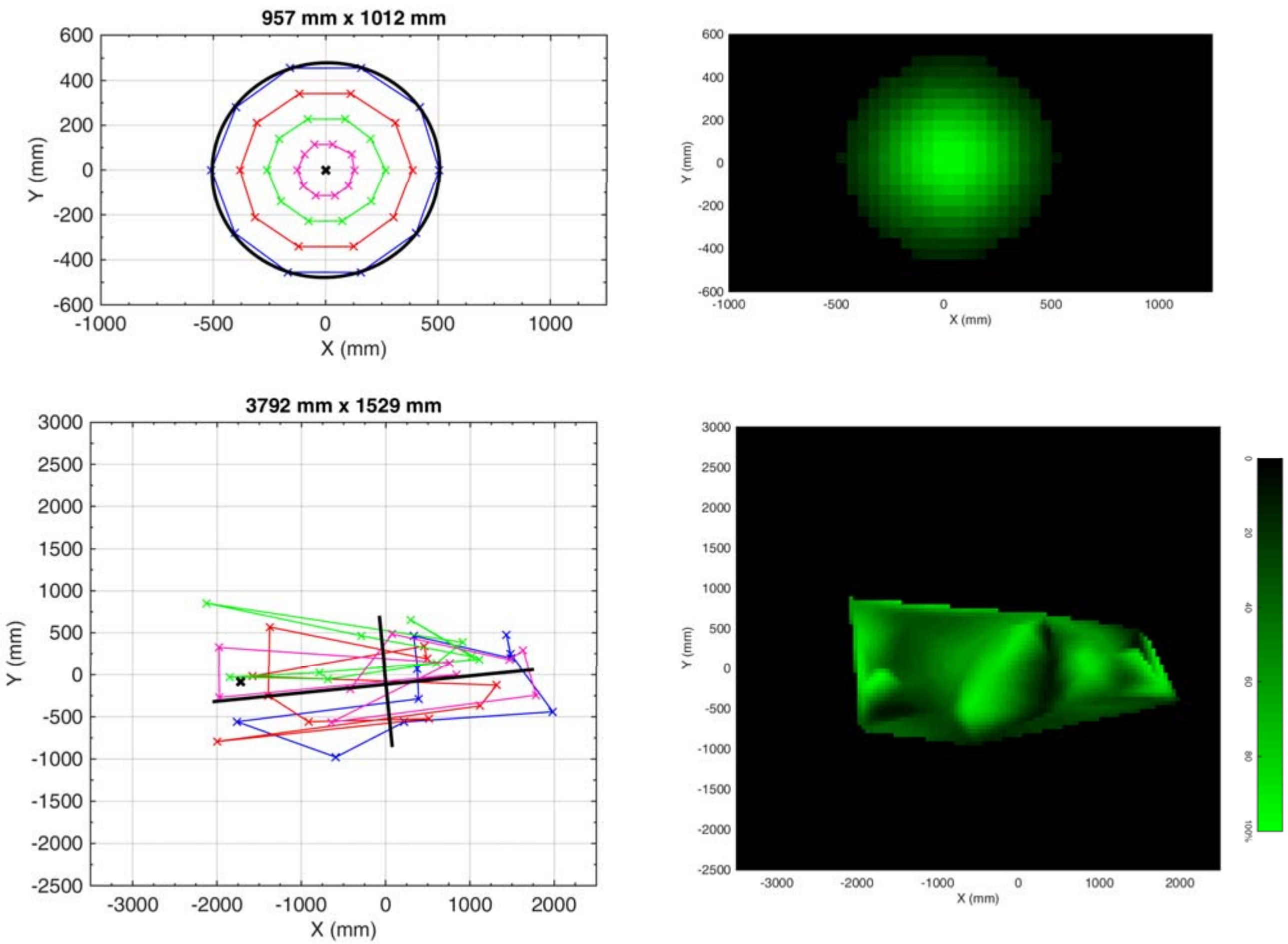




Changes in laser footprint size and shape

Calm, rippled sea with short but steep waves (Y1)

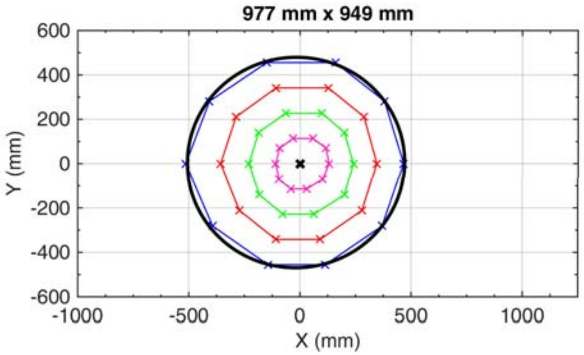
Expansion by **+3.2m in *X*** and **+0.8m in *Y*** @5m water depth

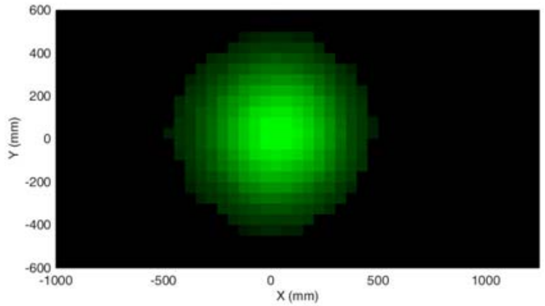


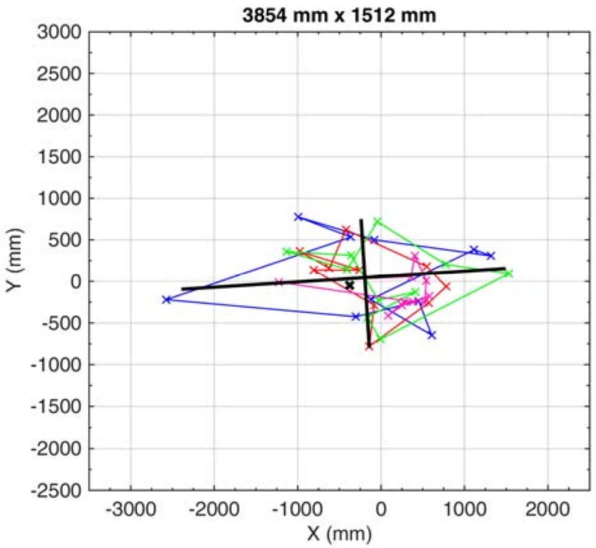
Changes in laser footprint size and shape

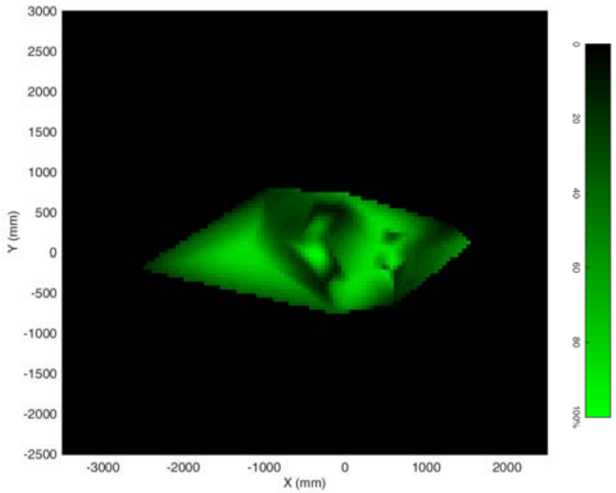
Smooth, shallow wavelets with small crests and troughs (Y2)

Expansion by ***+1.4m in X*** and ***+1.0m in Y*** @5m water depth





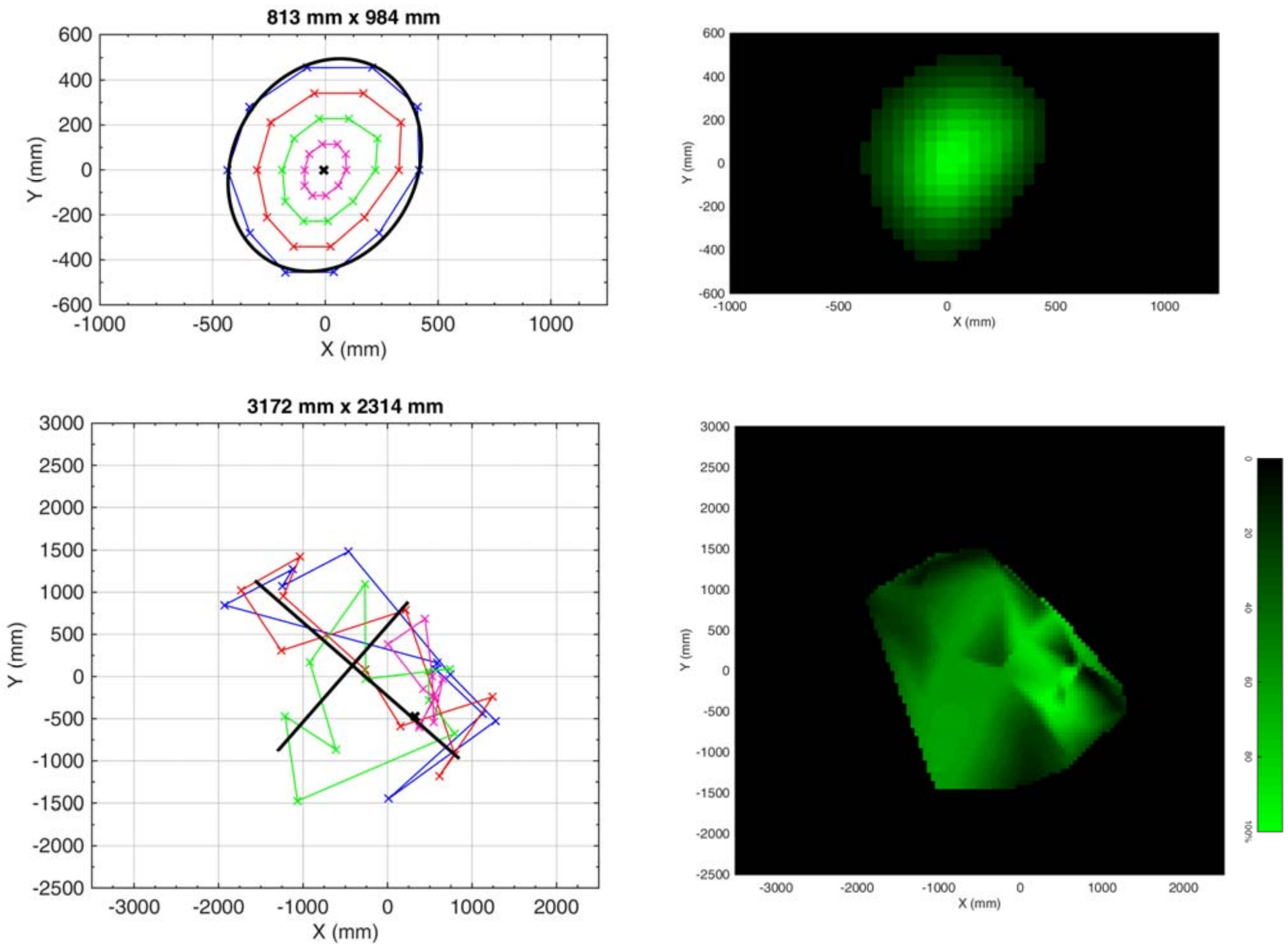




Changes in laser footprint size and shape

Moderate, long ocean waves (Y3)

Expansion by **+2.2m in *X*** and **+1.0m in *Y*** @5m water depth



Changes in laser footprint size and shape

Summary

- **Wave effects** will **influence** size, shape and intensity distribution of the **underwater laser pulse**
- On average, **most laser footprints are expanded**

- Expansion of 0.3% caused by beam divergence included
- Expansion/focusing depends on length and orientation of the waves as well as on flight and scan direction

Wave pattern	1^{st} PC – MajAx (%)			2^{nd} PC – MinAx (%)		
	min. / max. / **mean**					
Υ_1	39.6	89.1	**64.6**	3.2	28.0	**15.8**
Υ_2	12.4	57.5	**27.3**	-3.7	17.2	**3.3**
Υ_3	17.4	79.6	**43.9**	-0.5	42.7	**21.0**

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Conclusion and outlook

- Investigation of the effect of wave patterns on refraction and coordinate accuracy

- **The simplified assumption of averaging wave effects is not fulfilled**
- **Significant wave pattern dependent coordinate errors**

- Strictly applying corrections by **differential ray tracing for each laser pulse** → high resolution water surface modelling required
- Derive **correction terms** for typical wave patterns using the simulations at hand

- **More extensive simulations** varying beam divergence/aircraft altitude and beam deflection
- **Water surface modelling** from ALB data or other observations
- Acquisition of **ground truth data**

Underwater Data Acquisition and Processing

ISPRS Working Group II/9

Develop, evaluate and promote methods for underwater photogrammetry data acquisition and processing in the fields of environmental monitoring, heritage recording and industrial measurement.

Terms of Reference

- Definition of best practice for **geometric calibration**, color correction and validation of systems for underwater 3D measurements
- **Geometric and stochastic modeling** of multimedia geometry for underwater image and range measurements
- **Lidar bathymetry** for seafloor and water surface measurement
- Algorithms and methods for **underwater localization and navigation**
- Combined above water, through water and underwater techniques for **3D modeling of artefacts and mapping of coastal areas**

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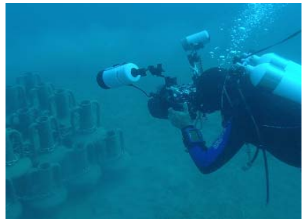
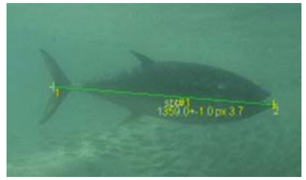
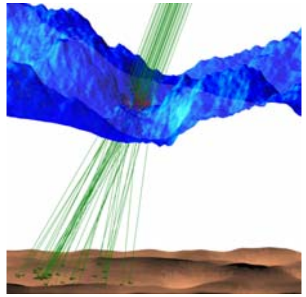
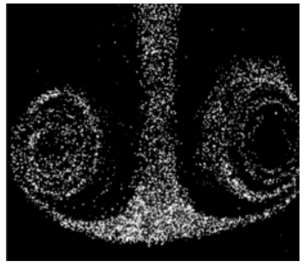
- Drop me a line → **patrick.westfeld@tu-dresden.de**









Thank You

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