TECHNISCHE UNIVERSITÄT DRESDEN

DRESDEN concept

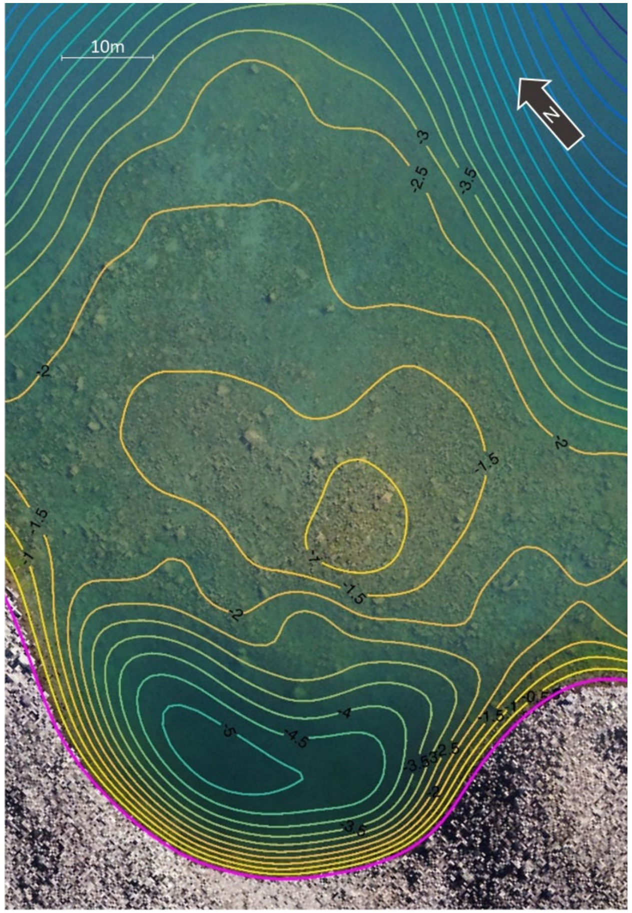
Institute of Photogrammetry and Remote Sensing

Methods for geometric modelling of refraction in photo-bathymetry

Christian Mulsow, 2024/11/7

Content

1. Introduction and Motivation
2. Modeling the Refraction - Ray Tracing
3. Integration in a Bundle Adjustment – Image Orientation
4. Underwater DTM extraction
5. Options and Limitations
6. Strategies for nonplanar water surfaces (waves)
7. Conclusion



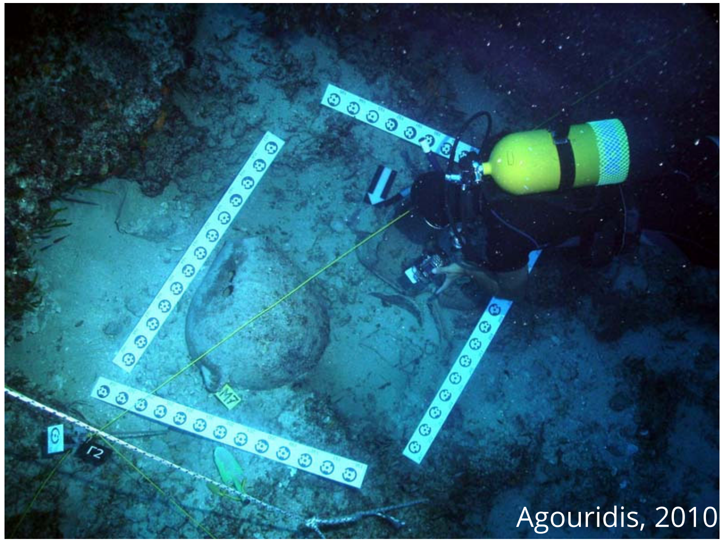
TECHNISCHE UNIVERSITÄT DRESDEN

DRESDEN concept

Introduction and Motivation

Photogrammetric measurement tasks in and through water -> from easy to difficult

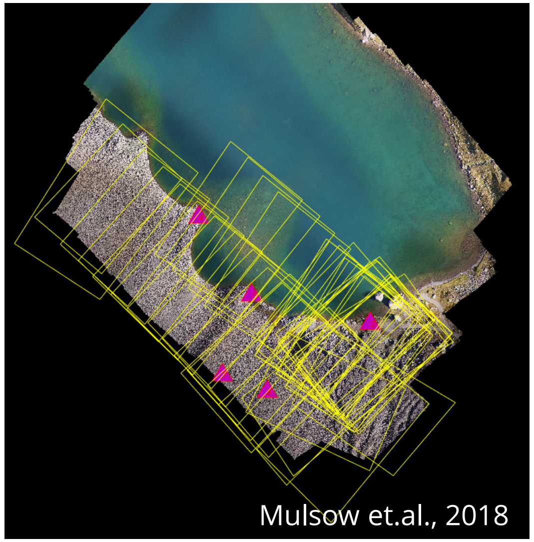
Underwater



Agouridis, 2010

Camera in a housing
(dome port – easy, flat port ~)

Through calm water



Mulsow et.al., 2018

Camera outside water
flat water surface

Through moving water

Andrew & Fonstad, 2007

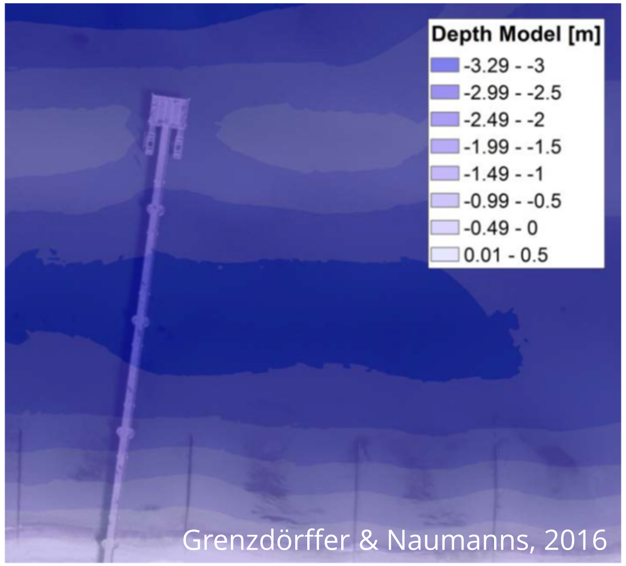
Camera outside water
wavy water surface

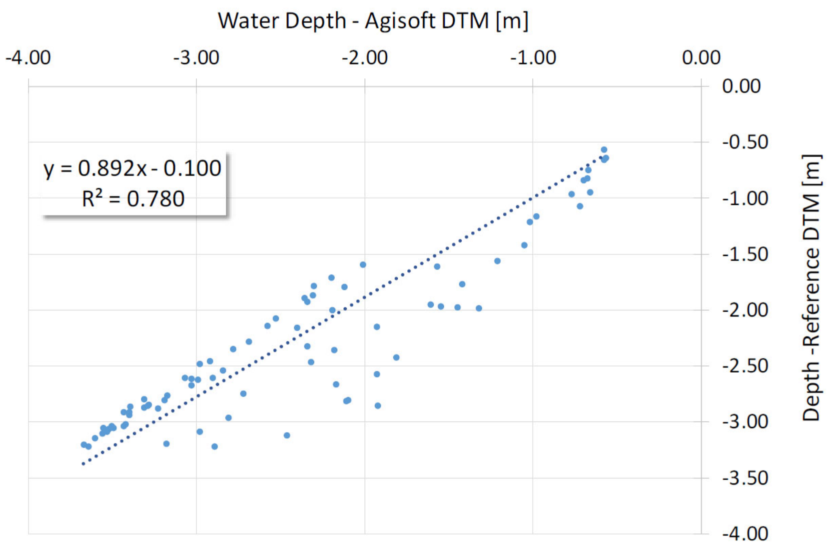
Introduction and Motivation

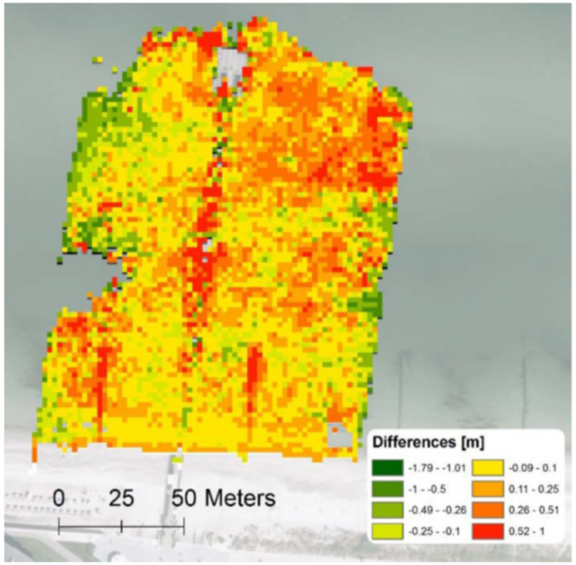
"practical" Approaches to compensate the refraction effects

- **Data processing in standard software (without refraction compensation)**
- **Option 1 : Linear regression - reference vs. measured heights**
- **Option 2 : Correction factor calculated from camera setup (flying height, focal length, base length**

Easy to implement, but low accuracy and reliability! –> Better: Geometric Modelling of refraction effects!





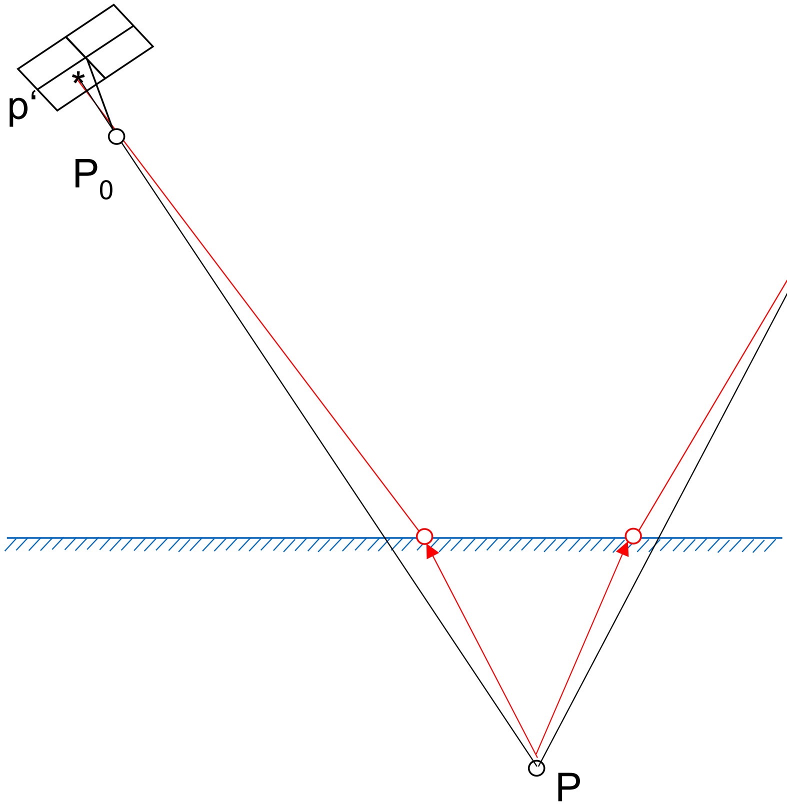


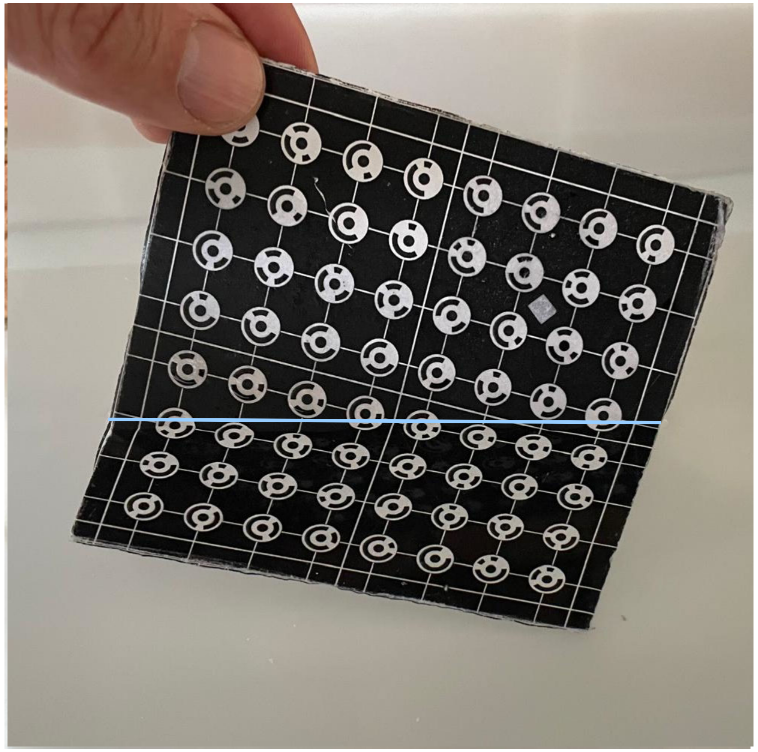
TECHNISCHE UNIVERSITÄT DRESDEN

DRESDEN concept

Modeling the Refraction

Standard pinhole-camera model without refraction





Standard collinearity equations system:

$$x' = x'_0 + z' \frac{r_{11}(X_P - X_0) + r_{21}(Y_P - X_0) + r_{31}(Z_P - X_0)}{r_{13}(X_P - X_0) + r_{23}(Y_P - X_0) + r_{33}(Z_P - X_0)} + \Delta x'$$

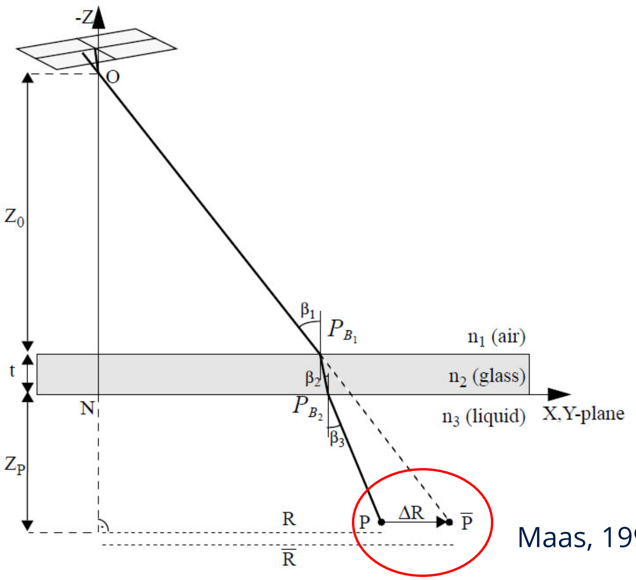
$$y' = y'_0 + z' \frac{r_{12}(X_P - X_0) + r_{22}(Y_P - X_0) + r_{32}(Z_P - X_0)}{r_{13}(X_P - X_0) + r_{23}(Y_P - X_0) + r_{33}(Z_P - X_0)} + \Delta y'$$

Modeling the Refraction

Compensation of the refraction effect by 'straightening' the image ray

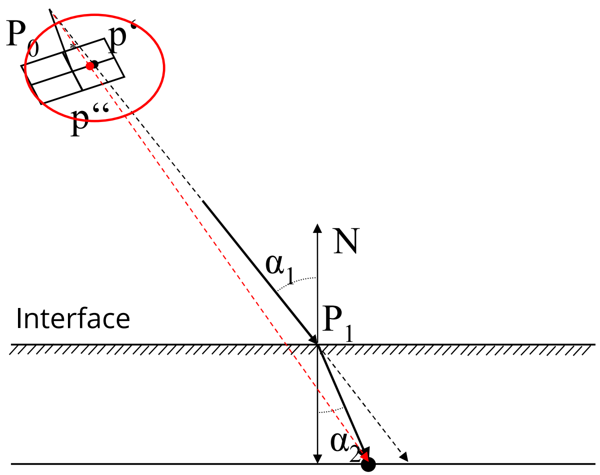
Possible strategies:

Shifting the object coordinates



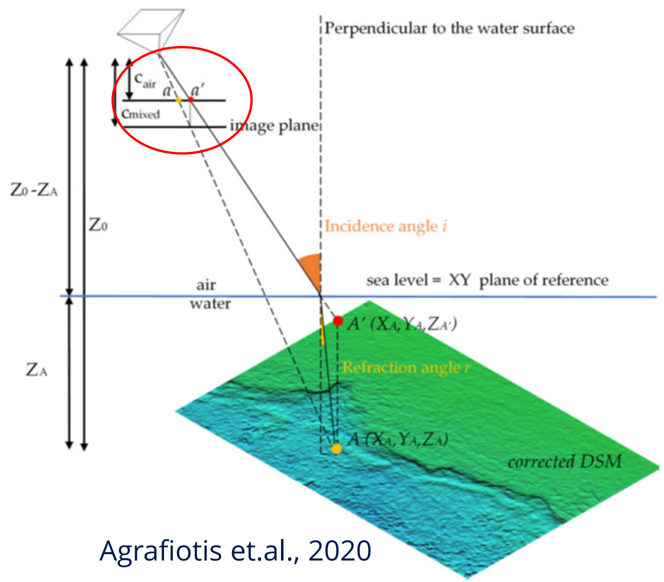
Maas, 1995

Shifting the image coordinates



Rinner, 1948

Shifting the focal length (c_k)

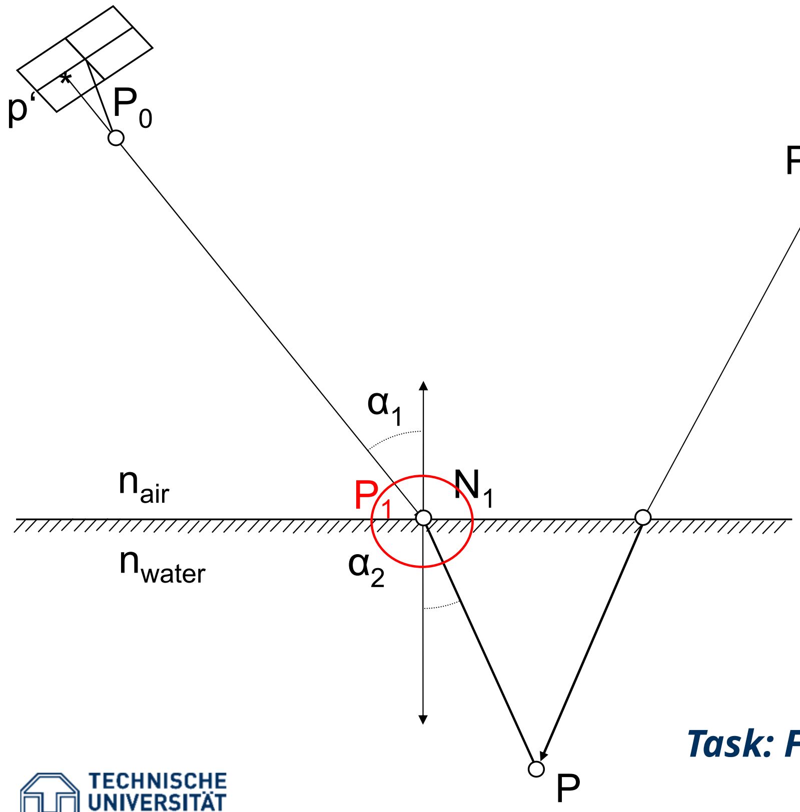


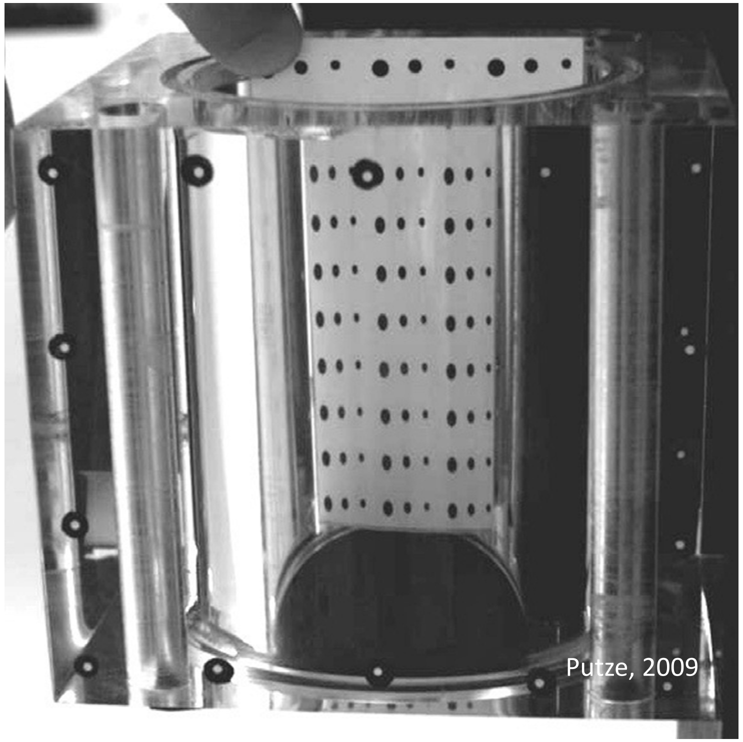
Agrafiotis et.al., 2020

Modeling the Refraction

Standard pinhole-camera model with refraction – universal model

First published by Kotowski, 1987





$$x' = x_0' + z'\frac{r_{11}(X_{P1} - X_0) + r_{21}(Y_{P1} - X_0) + r_{31}(Z_{P1} - X_0)}{r_{13}(X_{P1} - X_0) + r_{23}(Y_{P1} - X_0) + r_{33}(Z_{P1} - X_0)} + \Delta x'$$

$$y' = y_0' + z'\frac{r_{12}(X_{P1} - X_0) + r_{22}(Y_{P1} - X_0) + r_{32}(Z_{P1} - X_0)}{r_{13}(X_{P1} - X_0) + r_{23}(Y_{P1} - X_0) + r_{33}(Z_{P1} - X_0)} + \Delta y'$$

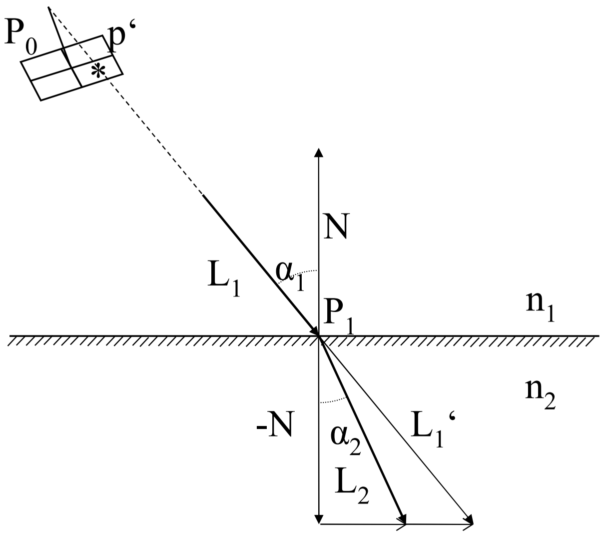
Task: Find the piercing point P_1 - Raytracing!

Modeling the Refraction

Raytracing

Forward ray tracing (FRT)

- **From image to object space**
- **For forward intersection**



FRT algorithm by Glassner (1989):

- *Piercing point via line surface intersection*
- *Refracted direction:*

$$L_{t+1} = \frac{L_t}{\boldsymbol{n_t}} + \left(\frac{C}{\boldsymbol{n_t}} - \sqrt{1 + \frac{1}{\boldsymbol{n_t}^2}(C^2 - 1)} \right) N_t$$

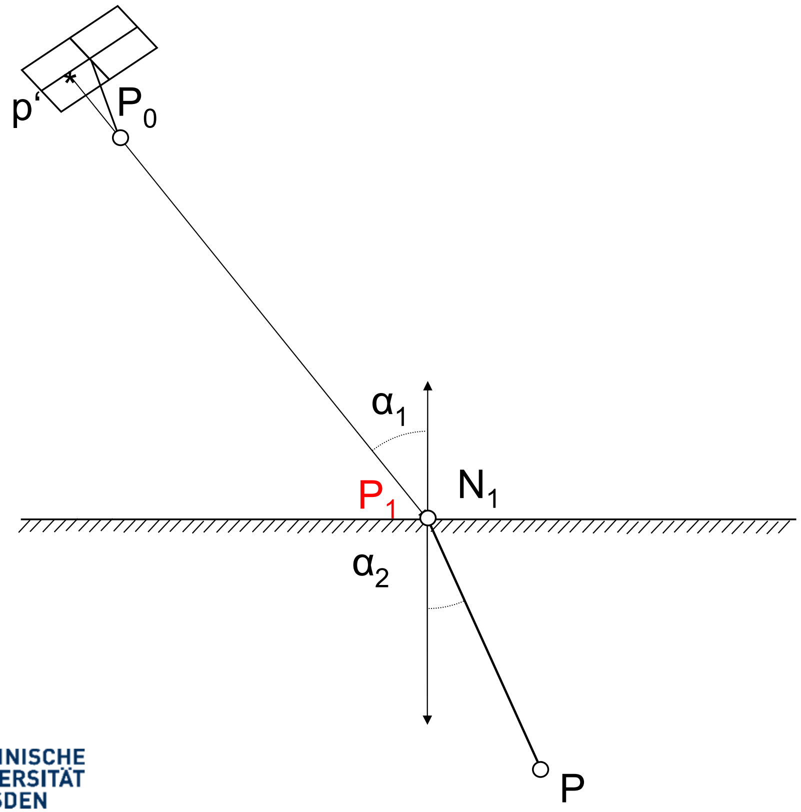
$$C = -N_t \cdot L_t \qquad , \quad \boldsymbol{n_t} = \frac{n_t}{n_{t+1}}$$

In case of multiple interfaces in the ray path, the refraction has to be computed sequentially!

Modeling the Refraction

Raytracing

Backward ray tracing (BRT)



Problem:

No initial direction of ray path !

Consequence:

No direct computing of ray path possible

Sequential computing impossible

Start values necessary

Solution:

Iterative solution of whole ray path

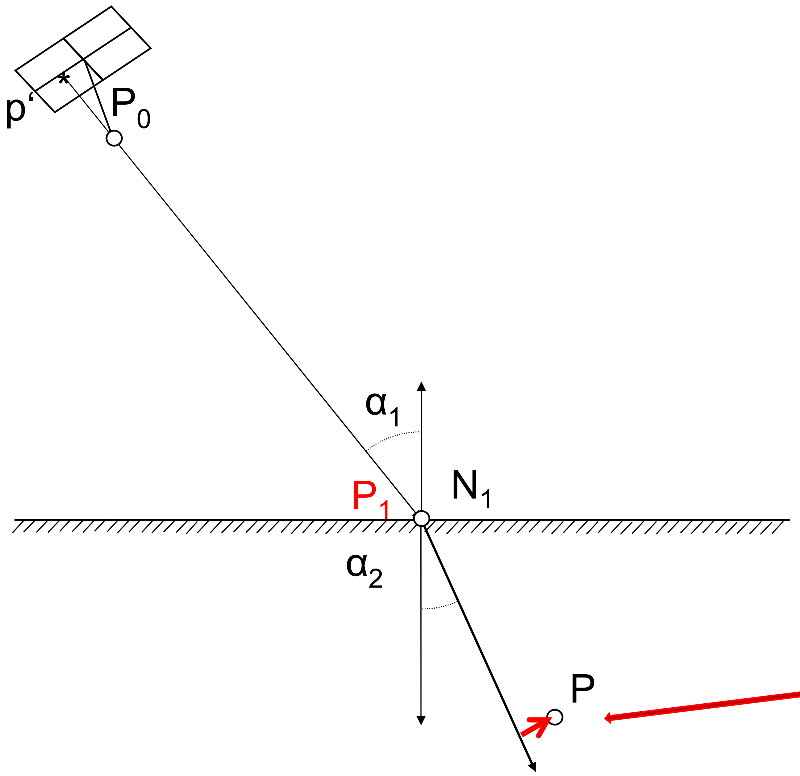
Different Approaches:

- Kotowski BRT
- Alternating forward ray tracing (AFRT)
- Minimum Distance Forward Raytracing (MDFRT)
- Scattershot (Brute Force)

(see Mulsow et. al, 2014, 'A universal approach for geometric modelling in underwater stereo image processing')

Modeling the Refraction

Backward Raytracing – different approaches - example



Minimum Distance Forward Ray Tracing (MDFRT)

- *Changing the start direction in order to minimize the distance of the image ray to object point P*
- *Based on forward ray tracing*
- *Conditional equation: distance = 0*

Input Data:

- *Object Point Coordinates P & P_0*
- *Surface model (parametric)*
- *Initial image ray direction*
- *initial surface point P_1 (From FRT)*
- *Surface Normal in initial surface point P_1 (From FRT)*
- *Refracted image ray direction (From FRT)*

$$\begin{bmatrix} X_d \\ Y_d \\ Z_d \end{bmatrix} = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} - \begin{bmatrix} X_t \\ Y_t \\ Z_t \end{bmatrix} - \frac{\begin{bmatrix} X_{Lt+1} \\ Y_{Lt+1} \\ Z_{Lt+1} \end{bmatrix} \cdot \left(\begin{bmatrix} X_t \\ Y_t \\ Z_t \end{bmatrix} - \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \right)}{\begin{bmatrix} X_{Lt+1} \\ Y_{Lt+1} \\ Z_{Lt+1} \end{bmatrix} \cdot \begin{bmatrix} X_{Lt+1} \\ Y_{Lt+1} \\ Z_{Lt+1} \end{bmatrix}} \begin{bmatrix} X_{Lt+1} \\ Y_{Lt+1} \\ Z_{Lt+1} \end{bmatrix}$$

Modeling the Refraction

Backward Raytracing – Integration in a Bundle Adjustment

Extended collinearity equations system:

$$x' = x'_0 + z' \frac{r_{11}(X_1 - X_0) + r_{21}(Y_1 - X_0) + r_{31}(Z_1 - X_0)}{r_{13}(X_1 - X_0) + r_{23}(Y_1 - X_0) + r_{33}(Z_1 - X_0)} + \Delta x'$$

$$y' = y'_0 + z' \frac{r_{12}(X_1 - X_0) + r_{22}(Y_1 - X_0) + r_{32}(Z_1 - X_0)}{r_{13}(X_1 - X_0) + r_{23}(Y_1 - X_0) + r_{33}(Z_1 - X_0)} + \Delta y'$$

Linearization only possible via numerical differentiation !

High computational effort!

Coordinates of the interface point **P_1** from Backward Raytracing :

$$\left(X_{1\,ij}^{\;l}, Y_{1\,ij}^{\;l}, Z_{1\,ij}^{\;l}\right) = f_{P_1}(X_{0j}, Y_{0j}, Z_{0j}, X_i, Y_i, Z_i, \boldsymbol{a}^l, \boldsymbol{n}^l)$$

in which:

- i = point index
- j = image index
- k = camera index
- t = interface index
- l = set of interface indices t
- a^l = set of interface parameters a_t
- n^l = set of relative refractive indices n_t

Modeling the Refraction

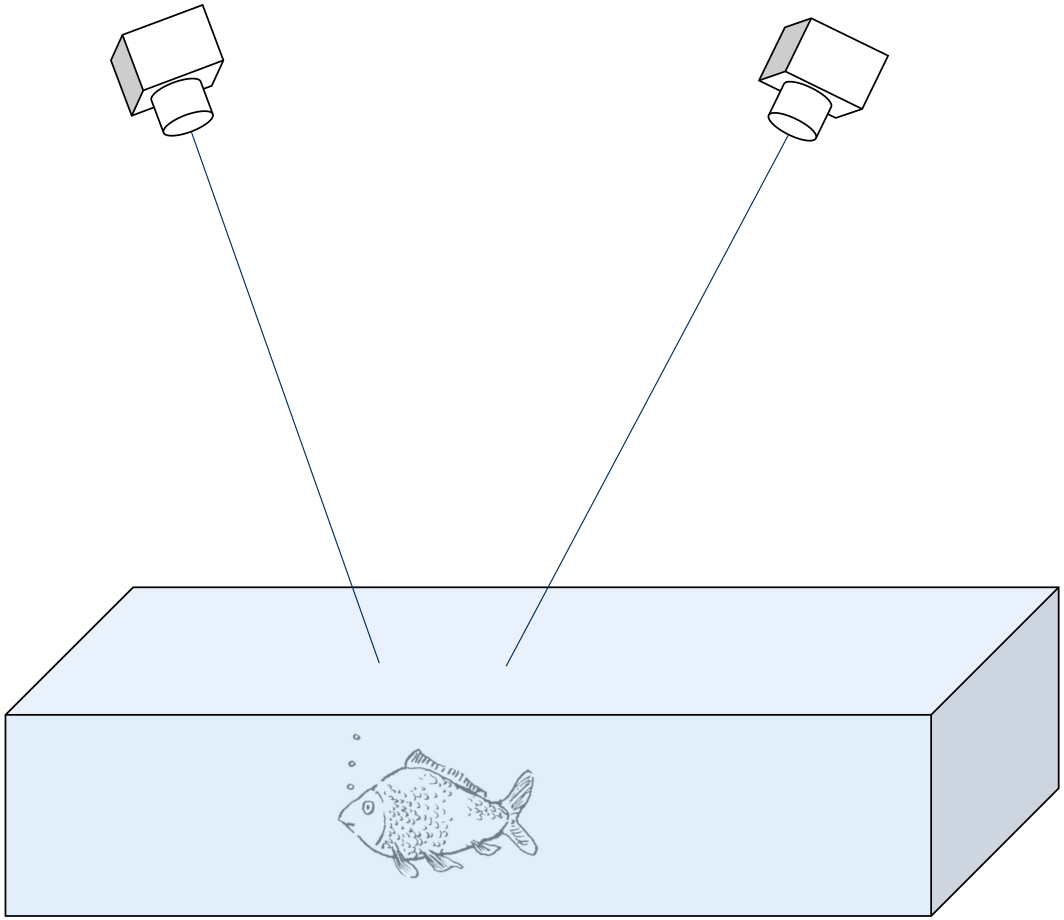
Integration in a Bundle Adjustment

Object invariant interface

1. Ray tracing -> calculation of P_t
2. Introducing P_t in collinearity equation

Interface parameters given in object coordinate system !

Normally the case with airborne photo-bathymetry !



Modeling the Refraction

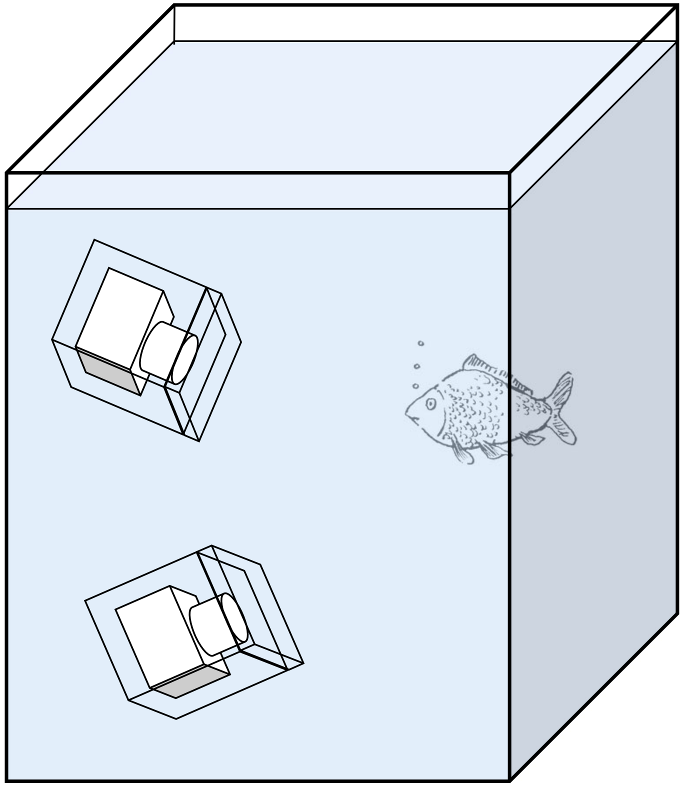
Integration in a Bundle Adjustment

Bundle invariant interface

1. Transformation of object point P in to the camera coordinate system
1. Ray tracing inside the camera system (port) -> calculation of P_{t*}
2. Transformation of P_{t*} back in to object coordinate system -> P_t
3. Introducing P_t in collinearity equation

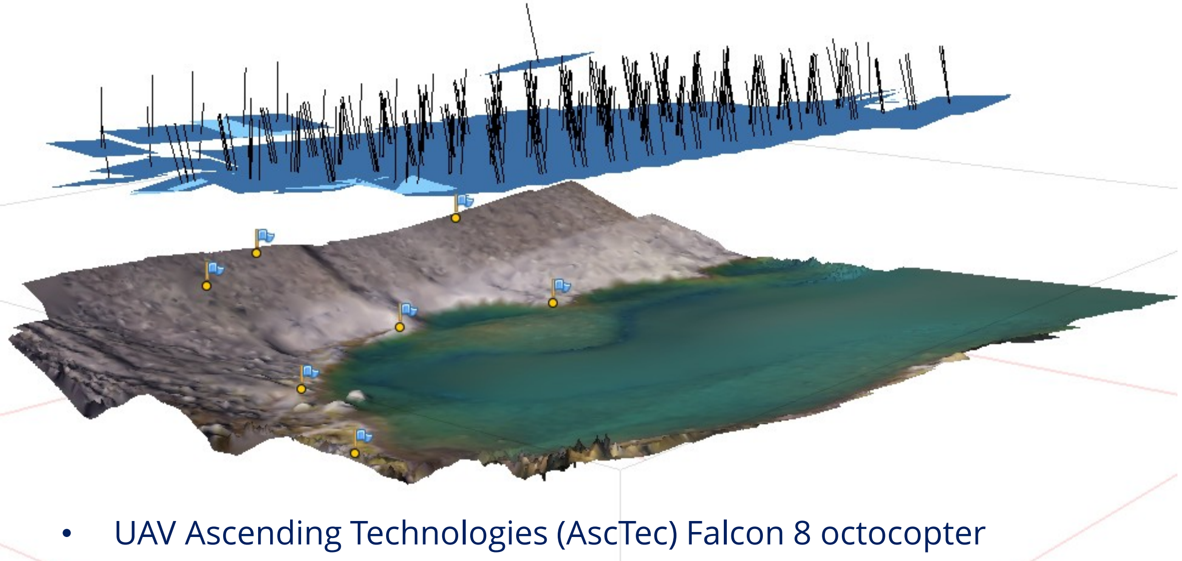
Interface parameters of the port (e.g. flat or dome) given in camera coordinate system !

Normally the case with underwater photogrammetry !



Modeling the Refraction

Multimedia Bundle Adjustment - Image Orientation - through water – example



- UAV Ascending Technologies (AscTec) Falcon 8 octocopter
- Sony NEX-7 camera (24 Mp, 20mm, F/2.8 optical lens)
- 300 images/ 100m flying height/GSD 2cm/ area 400x400 m²
- overlap 75% along track, 65% across track
- Orientations from UAV's GNSS/IMU, 8 control points on land (5/5/10cm)
- 70% water coverage

Adjustment

- fixed camera calibration parameters
- underwater-points together with onshore points
- Fixed water surface modelled as a plane

Result:

Parameter	Value
s_0	0.49 px
RMS x' y' land	0.42/0.43 px
RMS x' y' water	0.51/0.51 px
RMS X /Y/Z land	1.5/1.2/3.8 cm
RMS X/Y/Z water	0.9/1.6/5.3 cm
RMS Z of underwater check points	3.5 cm
RMS of underwater check points $Z_{reference}$-Z_{actual}	11.8 cm

TECHNISCHE UNIVERSITÄT DRESDEN

Modeling the Refraction

Multimedia Bundle Adjustment - pro's and con's

Options

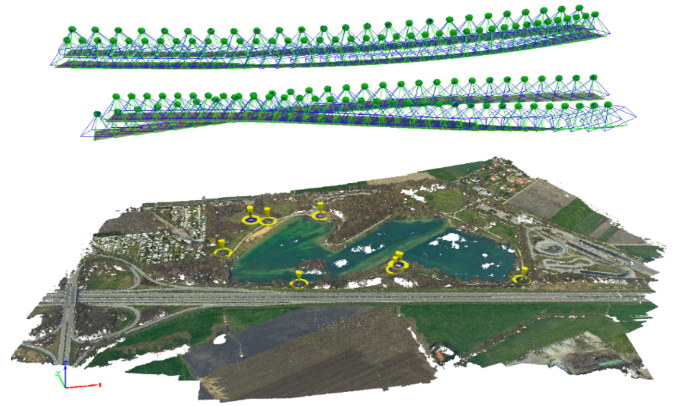
- Highly versatile
- All model parameters can be treated as unknowns (…camera orientations, shape of the water surface!)
- Constraints between the unknowns (e.g. parallelism of planes, membership of an object point to a surface etc.) can be defined

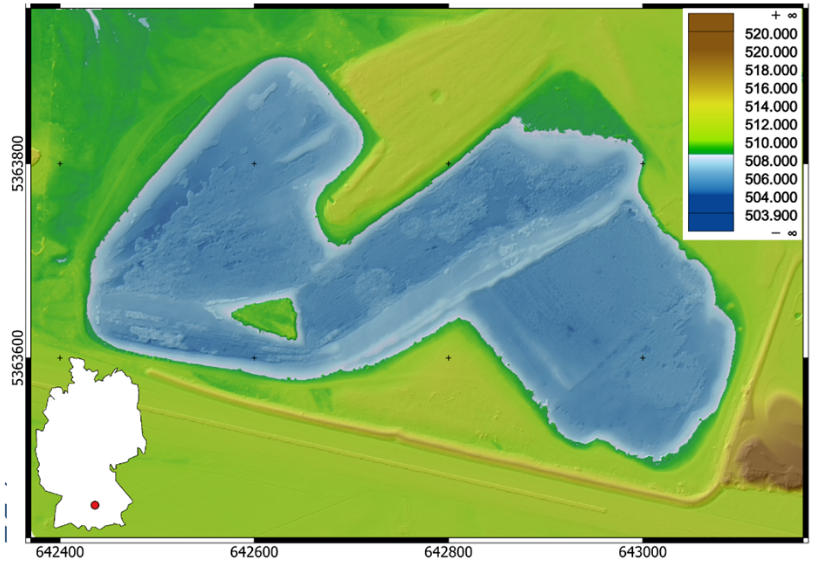
Limitations

- Combinations of unknown parameters may lead to singularity (e.g. all refractive indices are treated as unknowns)
- Stability of the adjustment depends on the imaging configuration and the distribution of control points (as usual…)
- Multi-media geometry requires a partly different view on the problem (new …)

Underwater DTM extraction

Examples - Autobahnsee, Augsburg, Bavaria, Germany



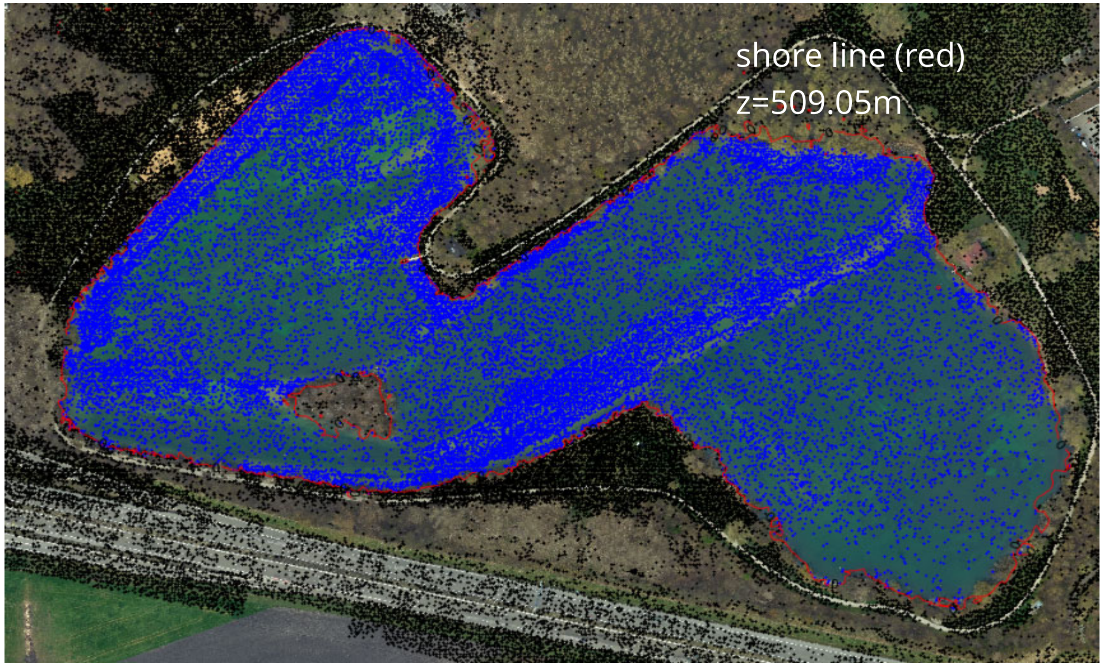


- IGI DigiCAM 100 camera, Orientations from GNSS/IMU
- 4 strips in two heights (450m/610) 61/65 images
- 90% overlap along track, 60% across track
- 10 control points (RTK GNSS)
- No underwater control points!

For evaluation: topo-bathymetrical laser scanner (Riegl VQ-880-G)

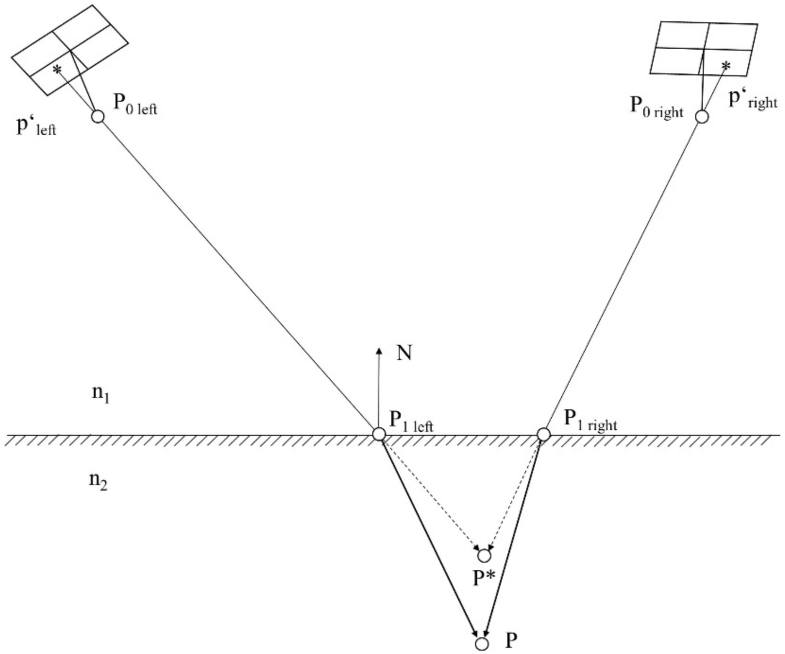
Underwater DTM extraction

Classification of land and water points – criteria point height



Matched points ● Land ● Water

Underwater DTM extraction



Processing of Stereo images

- Finding point pairs
- Matching
- Simple forward intersection
- Labelling of underwater points based on height
- 3D-coordinates via multimedia forward intersection
- Fusion of point-clouds
- Filtering
- TIN

Underwater DTM extraction

Examples Autobahnsee, Augsburg, Bavaria, Germany

Photo-DTM

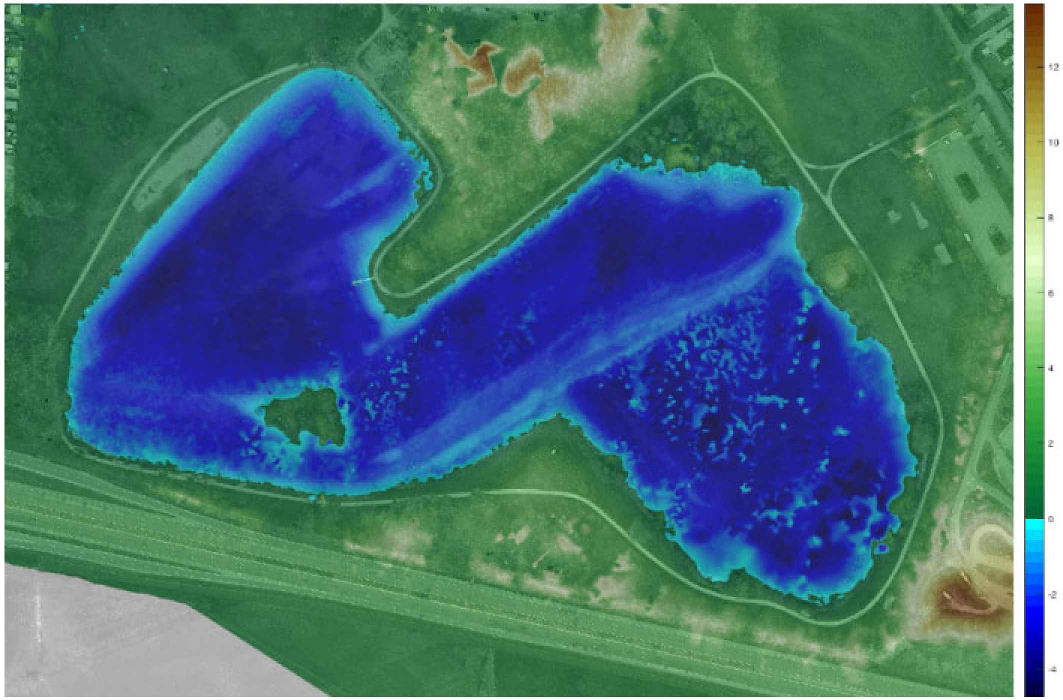
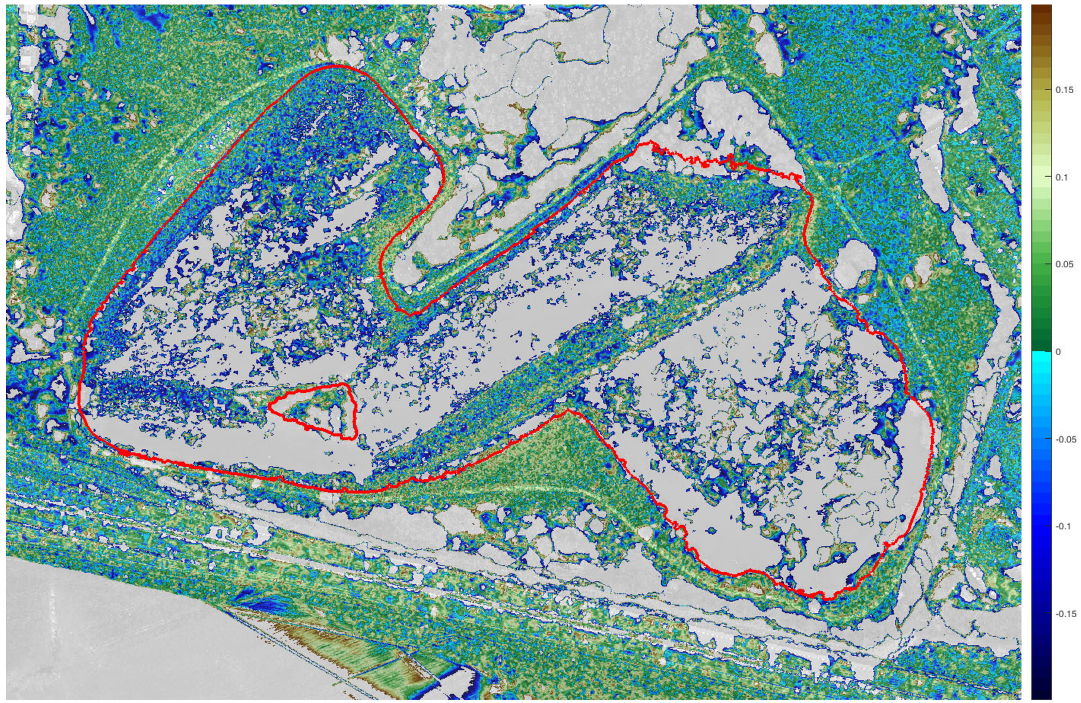
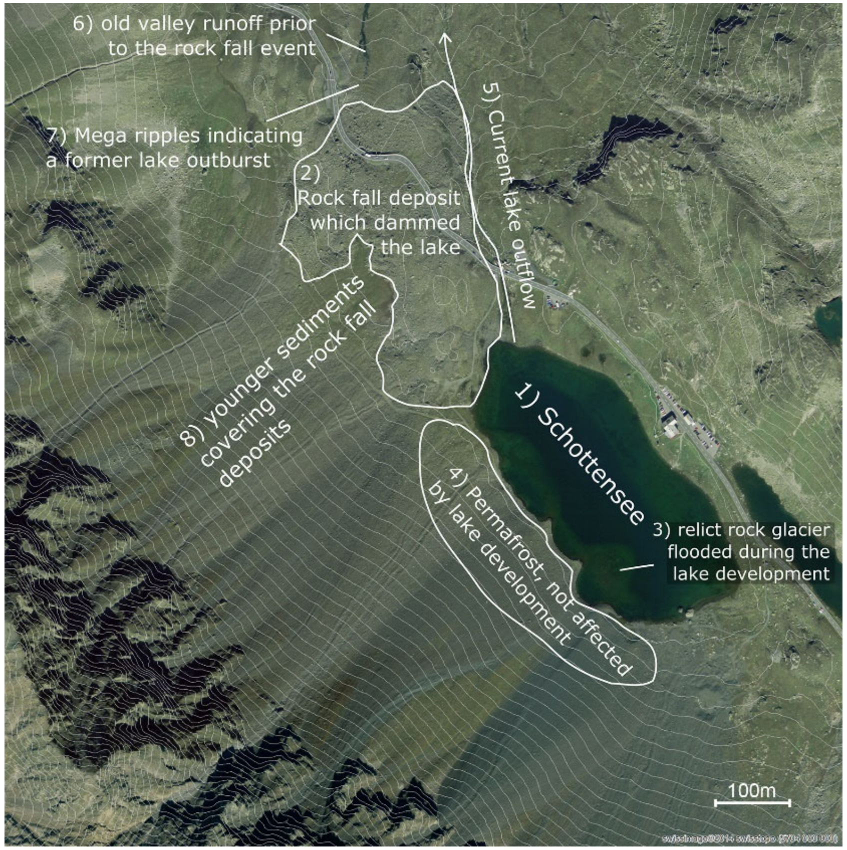


Photo vs. Laser[m]



Underwater DTM extraction

Examples - Lake Schottensee at Flüelapass



- UAV Ascending Technologies (AscTec) Falcon 8 octocopter
- Sony NEX-7 camera (24 Mp, 20mm, F/2.8 optical lens)
- 300 images
- 100m flying height
- GSD 2cm
- 75% overlap along track, 65% across track
- Orientations from UAV's GNSS/IMU
- 8 control points - accuracy 5/5/10 cm in X/Y/Z (on land)
- no underwater control points!
- 15 check points measured on lake bottom (accuracy 10/10/10 cm in X/Y/Z) - not signalized

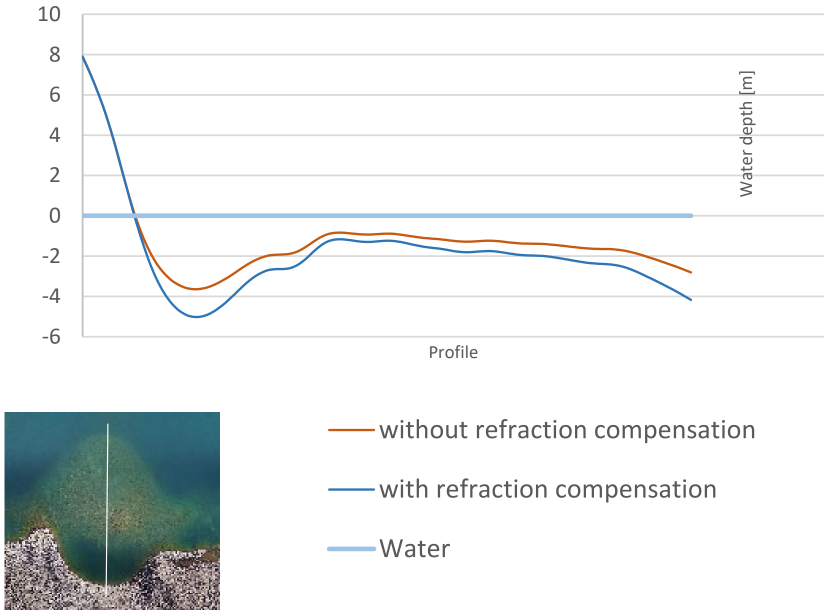
Underwater DTM extraction

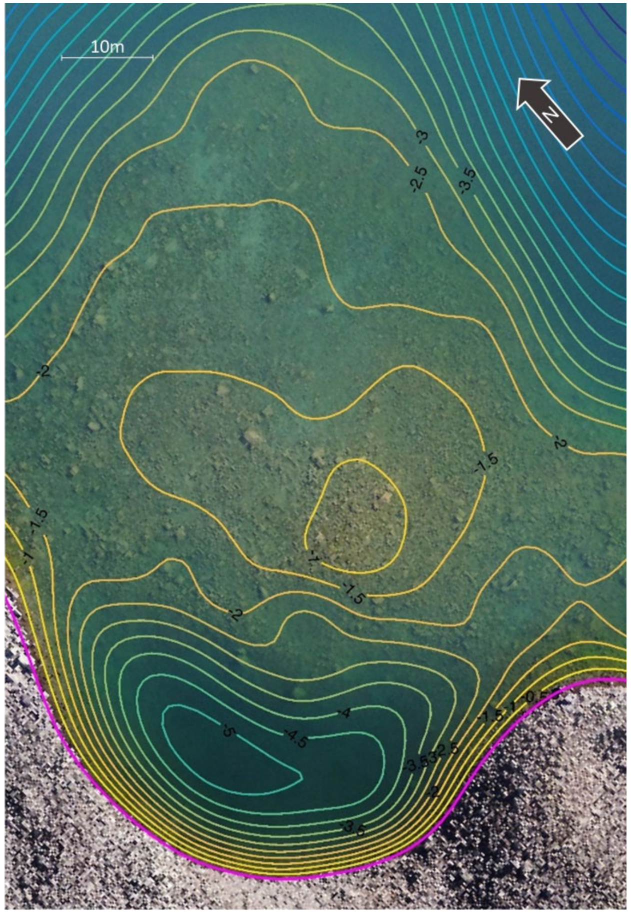
Examples - Lake Schottensee

RMS at underwater check points (13):

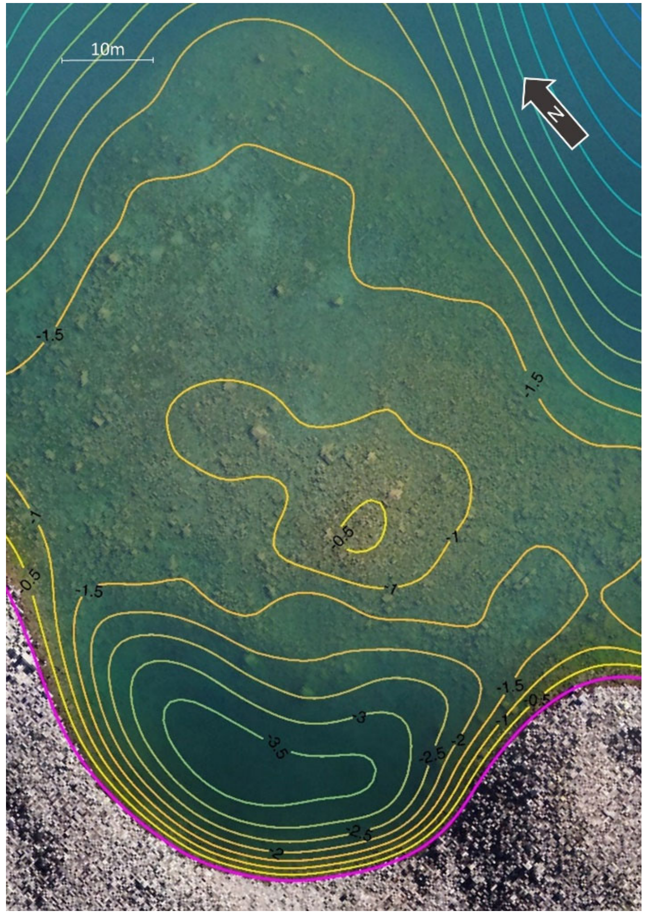
Z_{Actual}-$Z_{Reference}$ = 11.8cm

Inner accuracy (Z) = 3.5cm





With refraction compensation



Without refraction compensation

Conclusion and Outlook

- Refraction compensation is necessary and possible
- DEM Quality depends on imaging quality
- Actually limited to quite water surface (water surface modelled as flat horizontal plane)

Future

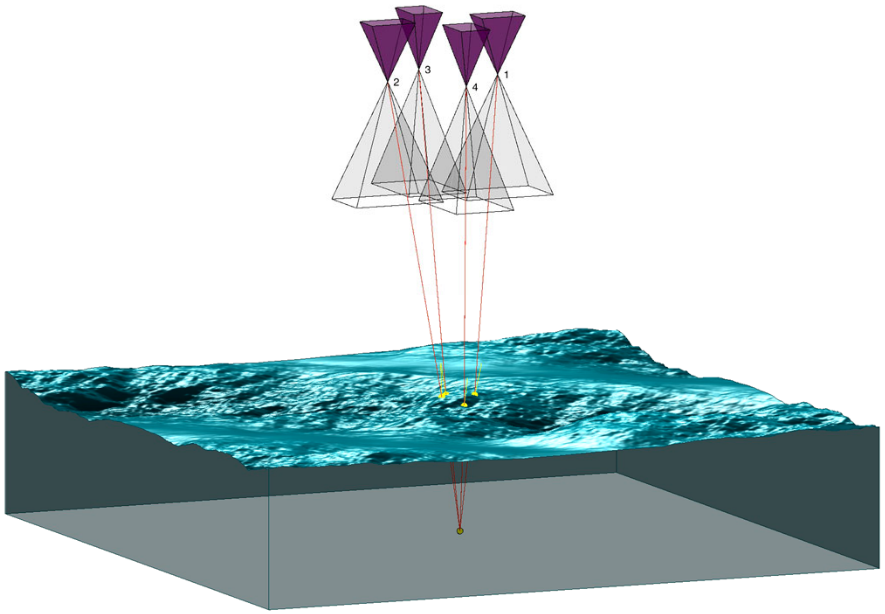
- Automatic shore line extraction
- Imaging through wavy surfaces

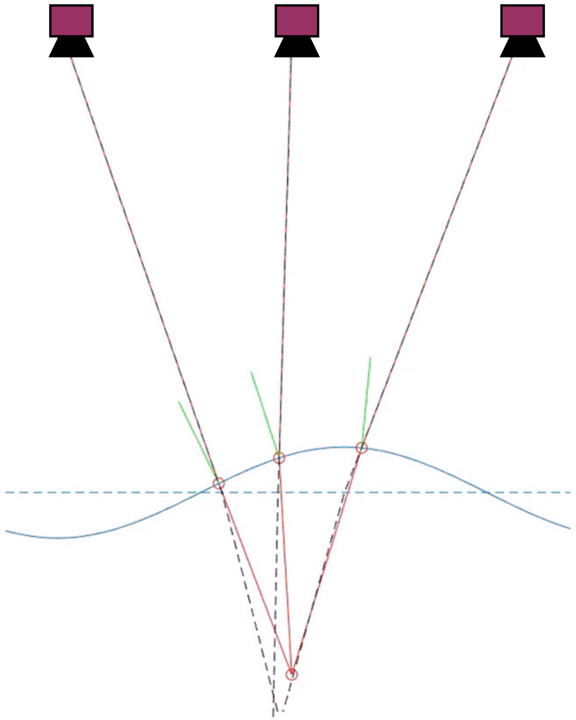
Conclusion and Outlook

Strategies for wavy water – taking image sequences

Complex method:

- Spatio-temporal Modelling of water surface



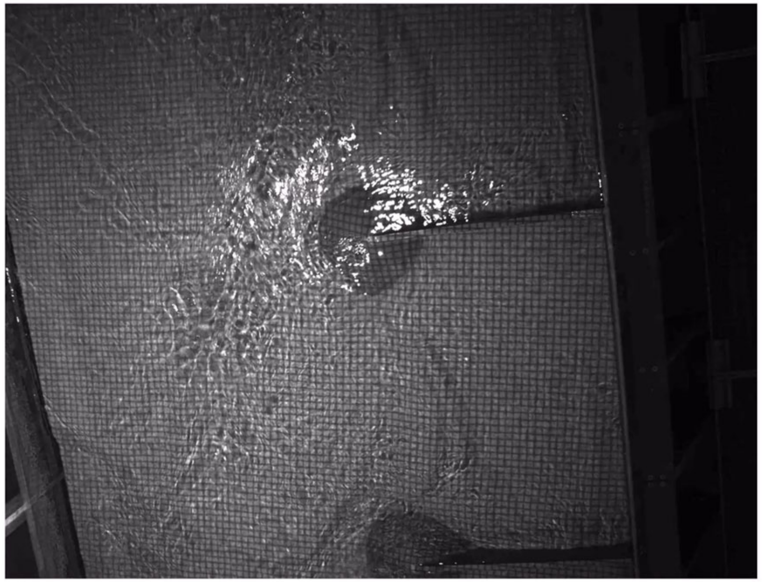


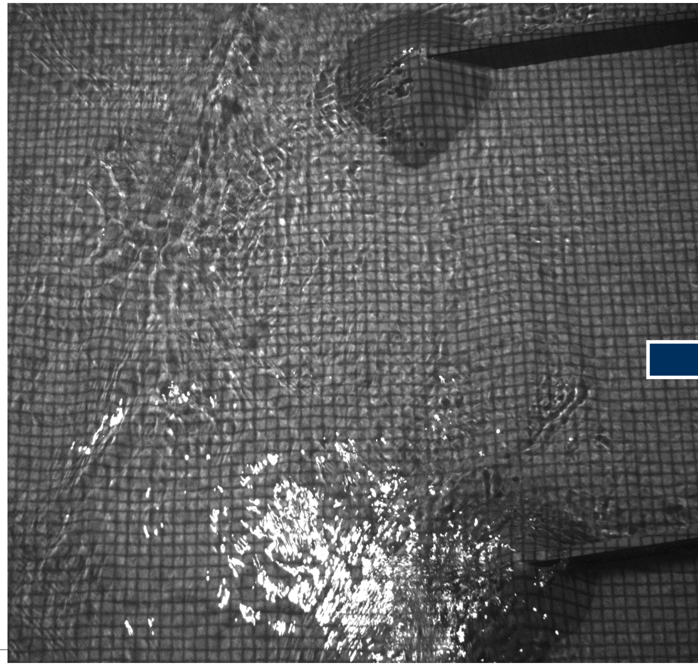
Conclusion and Outlook

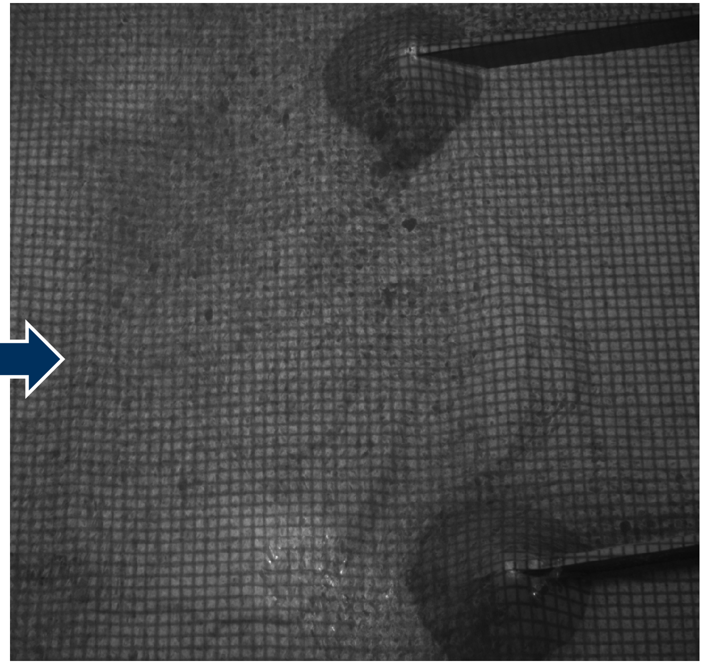
Strategies for wavy water – taking image sequences

Simple Method:

- pixel-wise median-filtering → Result: 'corrected' image corresponding to a image taken through flat calm water







Questions?

Christian Mulsow
christian.mulsow@tu-dresden.de