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THE USE OF TERRESTRIAL LASER SCANNING FOR MEASUREMENTS IN SHALLOW-WATER: CORRECTION OF THE 3D COORDINATES OF THE POINT CLOUD

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ABSTRACT

Although acoustic measurements are a wide-spread technique in the field of bathymetry, most systems require a water depth of at least 2 m. Furthermore, mapping shallow-water depths with acoustic techniques is expensive and complicated. Over the last decades, the use of laser scanning for mapping riverbeds has increased. However, the level of accuracy and the point density which can be obtained by Airborne Laser Scanning (ALS), and Airborne Laser Bathymetry (ALB) in particular, are not as high as those of terrain measurements originating from ALS. Moreover, ALS and ALB are not yet suited for mapping shallow-water beds.

Therefore, more recent research focuses on the use of Terrestrial Laser Scanning (TLS) from either a fixed or static position (STLS) or from a mobile platform (MTLS). An obvious advantage of using STLS and MTLS is that both the river beds and the river banks can be modelled by means of the same data acquisition system. This ensures a seamless integration of data sets describing both dry and wet surfaces, and thus of topography and bathymetry. However, although STLS and MTLS have the potential to produce high resolution point clouds of shallow-water riverbeds and -banks, the resulting point clouds have to be corrected for the systematic errors in depth and distance that are caused by the refraction of the laser beam at its transition through the boundary of air and water.

In this research a procedure was implemented to adjust the coordinates of every point situated beneath the water surface, based on the refractive index. The refractive index depends on the wavelength of the laser beam and the properties of the media the beam travels through. The refractive index for a laser beam with a wavelength of 532 nm varies by less than 1% for a wide range of temperature and salinity conditions. Nevertheless, during the case studies, it became clear that it is important to use an estimate of the refractive index which approaches the actual value as closely as possible in order to obtain accuracies of less than 1 to 2 cm. Therefore, the refractive index was determined for each specific case by using water samples.

Keywords: terrestrial laser scanning, bathymetry, coordinate transformation, refractive index, through-water laser scanning

INTRODUCTION

Although acoustic measurements are a wide-spread technique in the field of bathymetry, most systems require a water depth of at least 2 m. Furthermore, mapping shallow-water depths with acoustic techniques is expensive and complicated because of the impact of parameters such as turbulence, water clarity, wave height, suspended particles [1]. Additionally, the swath width of shallow-water multibeam sonar becomes very narrow, which results in more surveying strips and processing work.

Another problem that may occur concerns the integration of topographic and bathymetric surveys. The use of different data acquisition techniques for dry and submerged surfaces implies the use of different reference systems, which can lead to data gaps or inconsistencies along coastal strips and river banks [2].

Over the last decades, the use of laser scanning for mapping riverbeds has increased. However, the level of accuracy and the point density which can be obtained by Airborne Laser Scanning (ALS), and Airborne Laser Bathymetry (ALB) in particular, are not as high as those of terrain elevation measurements originating from regular topographic ALS. Moreover, ALS and ALB are not yet suited for mapping shallow-water beds. Therefore, more recent research focuses on the use of Terrestrial Laser Scanning (TLS) from either a fixed or static position (STLS) or from a mobile platform (MTLS). [3] Notwithstanding data loss due to the reflection of the laser beam at the water surface and the absorption and the dispersion of the laser beam passing through the water, TLS has the potential to produce high density point clouds of shallow-water riverbeds with a high level of detail [4], [5].

An obvious advantage of using STLS an MTLS is that both the river beds and the river banks can be modelled by means of the same data acquisition system. This ensures a seamless integration of data sets describing both dry and wet surfaces, and thus of topography and bathymetry. However, before registration, the resulting point clouds have to be corrected for the systematic errors in depth and distance that are caused by the refraction of the laser beam at the interface between air and water. [4], [5]

METHODOLOGY

In this research a procedure was implemented to adjust the coordinates of every point situated beneath the water surface based on the refractive index.

The effect of the refraction depends on the angle of incidence between the laser beam and the air-water interface, the distance the beam travels under water and the refraction index. This typically results in an elongation of the distance measurement and thus also in an over- or underestimation of the depth. (Figure **2**)

The coordinates of the points obtained by the scanner are defined in a reference system connected with the centre of the instrument. The transmission centre is the origin with coordinates (0,0,0). If the instrument is levelled, the z-axis is vertical. The x- and y-axes are perpendicular to each other and to the z-axis and form the horizontal reference plane. During the scanning process the x-, y-, z- coordinates are calculated from the measured distance (d_{tot}) between the scanner and the object and the corresponding measured angles θ and φ. φ is zero in the x-direction and is positive counter clockwise; θ is the zenith angle. This is illustrated in Figure 1.

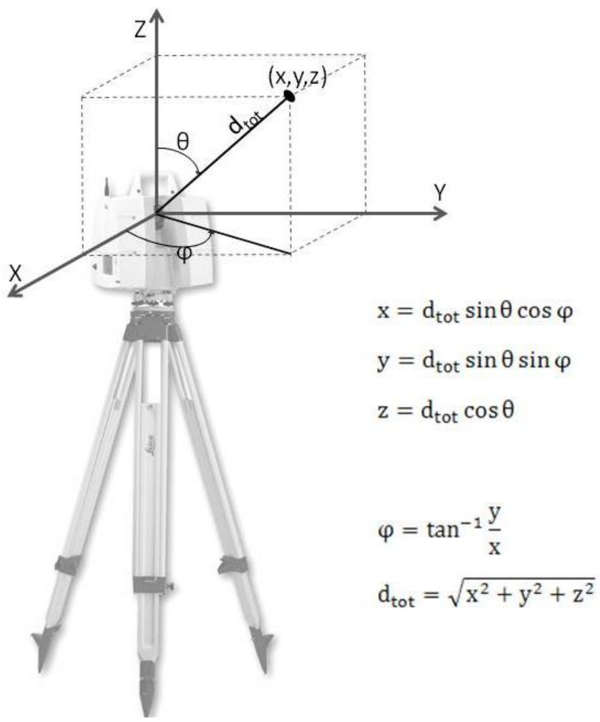

Figure 1: Scanner reference system and point coordinates

For the calculation of the coordinates, the scanner assumes that the path of the laser beam is a straight line and that the laser signal travels at a constant speed. However, when the laser beam encounters and travels through a medium with a different refraction index (e.g. glass window, water), the angle of the laser beam and its velocity are altered and thus also the acquired coordinates.

To be able to recalculate the coordinates of points below the water surface, following parameters have to be known (Figure **2**):

- the vertical distance (h) between the scanner origin (x_0,y_0,z_0) and the water surface,
- the relative refractive index (n) from air to water for the wavelength of the laser beam,
- the angle of incidence (i) and the angle of refraction (r),
- the coordinates of the point where the laser beam enters the water.

The vertical distance (h) between the scanner origin and the water surface has to be measured. Depending on the circumstances, this can be done manually or by using the point cloud.

The relationship between the angle of incidence (i) and the angle of refraction (r) is given by the law of Snellius-Descartes:

$$n = \frac{\sin i}{\sin r} \tag{1}$$

where n is the refractive index, i is the angle of incidence and r is the refractive angle.

The refractive index (n) is dependent on the properties of the optical media the electromagnetic wave travels through, the temperature, the atmospheric pressure and the wavelength of the electromagnetic wave. n can be interpolated from the tables published by Daimon and Masumura [6]. Based on these tables, the interpolated refractive index for a laser beam with a wavelength of 532 nm travelling from air to distilled water varies from 1.335546 at 19°C to 1.335065 at 24°C for an atmospheric pressure within the range from 989 to 1000 hPa.

The angle of incidence (i) is the angle between the normal on the water surface (= vertical, when assuming a flat water surface) and the laser beam.

$$i = \arccos \frac{z}{d_{tot}} \tag{2}$$

As the angle of incidence of the laser beam is different for each measured point, the angle of refraction (r) is also different for each point of the point cloud. Therefore, for the submerged area, the angle of refraction has to be calculated for each point in order to be able to recalculate the correct position of the points. Substitution of the value for i derived from equation (2) in equation (1) allows the calculation of the angle of refraction:

$$r = \arcsin \left(\frac{\sin i}{n} \right)$$

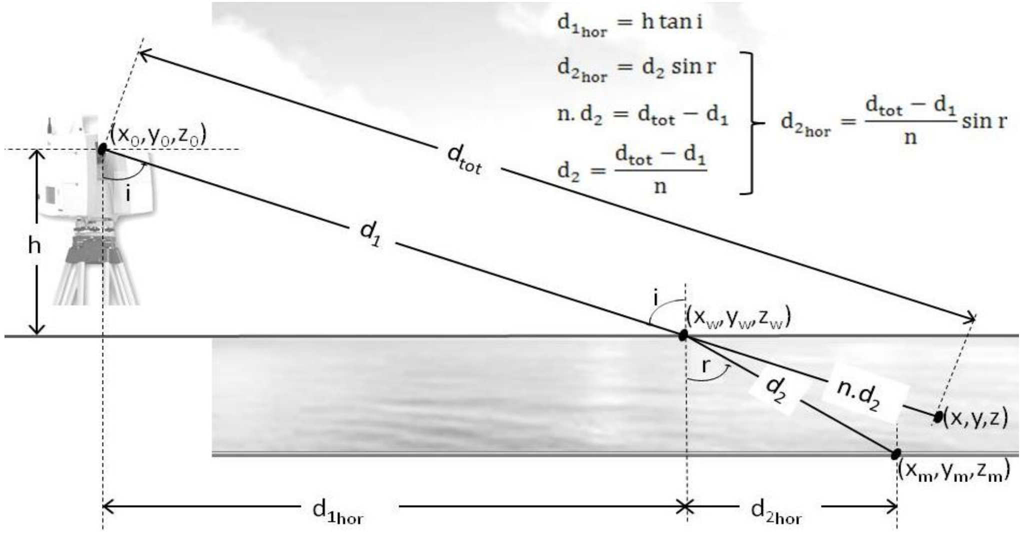

Figure 2: Relation between the parameters needed for the correction of the coordinates of points below the water surface

The coordinates of the points where the laser beam enters the water (x_w,y_w,z_w) are needed to determine the distance the electromagnetic signal travels under water. They are function of the relative height between the scanner and the water surface (h), the angle of incidence (i) (Figure **2**), and the angles θ and φ (Figure 1). Equations (3) allow the calculation of x_w, y_w and z_w.

$$x_w = \frac{h}{\cos i} \sin\theta \cos\varphi$$
$$y_w = \frac{h}{\cos i} \sin\theta \sin\varphi \qquad (3)$$
$$z_w = -h$$

Finally, based on Figure **2**, the modified real coordinates of the submerged points (x_m,y_m,z_m) can be calculated as follows:

$$x_m = x_w + d_2 \sin r \cos\varphi = x_w + \frac{d_{tot} - d_1}{n} \sin r \cos\varphi$$
$$y_m = y_w + d_2 \sin r \sin\varphi = y_w + \frac{d_{tot} - d_1}{n} \sin r \sin\varphi \qquad (4)$$
$$z_m = (-1)(d_2 \cos r + h) = (-1)\left(\frac{(d_{tot} - d_1)\cos r}{n} + h\right)$$

where:

$$d_1 = \sqrt{x_w^2 + y_w^2 + z_w^2}$$
$$d_{tot} = \sqrt{x^2 + y^2 + z^2}$$

RESULTS

The methodology described in the previous section was programmed in a Python script. The procedure was validated by means of several case studies in which a pulse laser scanner (Leica Scanstation C10) with a laser beam wavelength of 532 nm was used because of its high penetration capacity.

Figure 3 and Figure 4 show the results of the scan of a swimming pool. The correction procedure must be performed before the registration of the point clouds, because the local coordinate system of the laser scanner is used.

During the correction procedure, the coordinates of points situated above the water surface are not adapted.

The difference between the calculated depths and the real depths varied from less than 1 cm to 2 cm depending on the travelling distance of the laser beam under the water surface, the angle of incidence and the relative refraction index.

In Figure 3, a vertical slice of the point clouds before and after correction is shown. Both point clouds are merged in Figure 4. The figures clearly show that the displacement of the original point cloud occurs not only in the vertical direction.

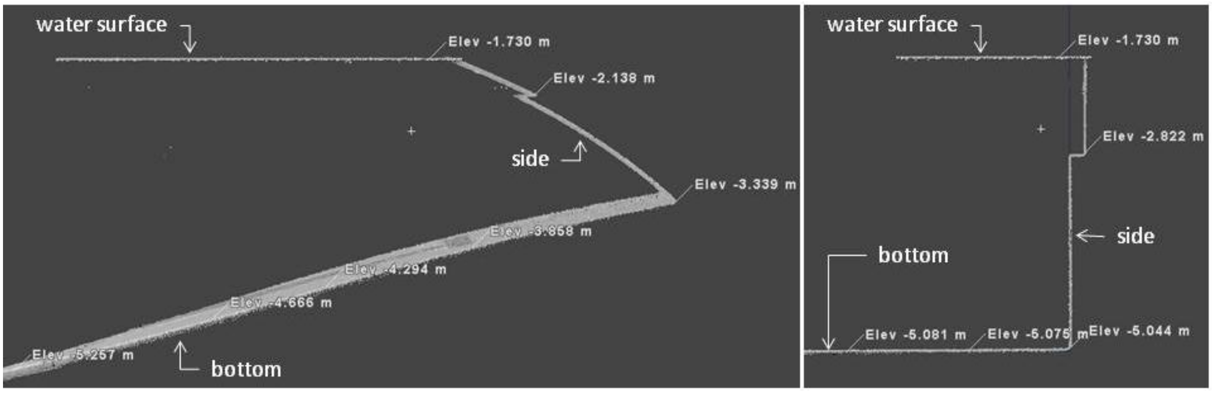

Figure 3: Swimming pool - vertical slice of the point cloud before (left) and after (right) the transformation of the points beneath the water surface

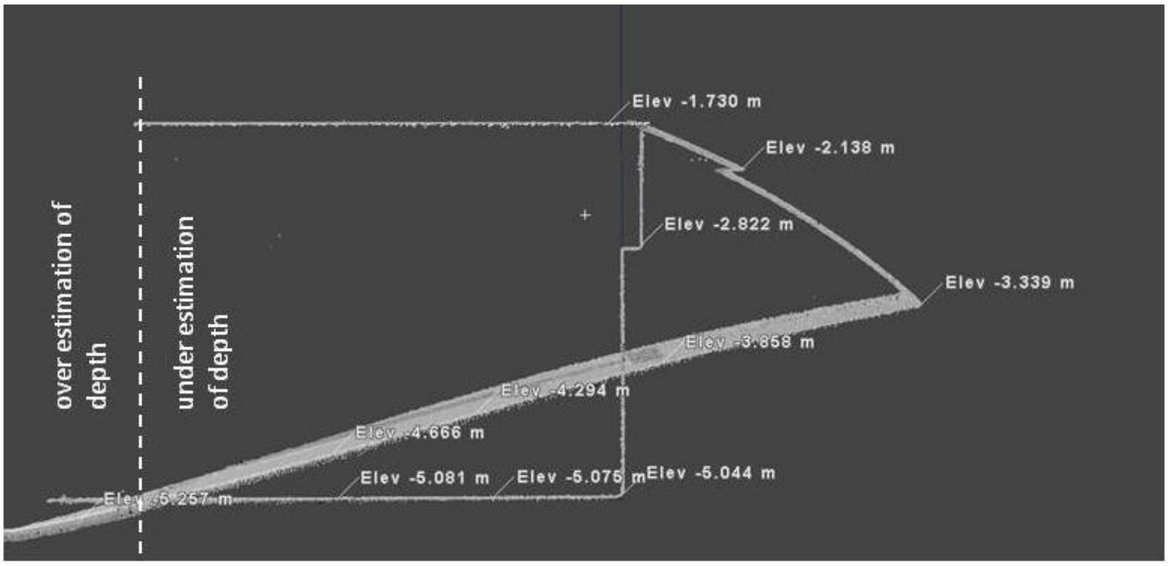

Figure 4: Swimming pool - the vertical slices of both point clouds (before and after transformation) merged together

CONCLUSION

The refractive index depends on the wavelength of the laser beam and the properties of the media the beam travels through. Although the refractive index for a laser beam with a wavelength of 532 nm varies by less than 1% for a wide range of temperature and salinity conditions [7], during the case studies, it became clear that even small variations of n can result in depth variations of several centimetres in function of the angle of incidence. Therefore, it is important to use an estimate of the refractive index which approaches the actual value as closely as possible in order to obtain accuracies of less than 1 to 2 cm. During the case studies the refractive index was determined for each specific case by using water samples.

The ideal conditions of the case studies are not likely to occur in the field. In the case of the swimming pool, the water was clear, free of turbulence or currents, there was no wind so the water surface was flat and did not influence the angle of incidence. Furthermore, the material of the bottom and sides of the swimming pool were highly reflective. Hence, more tests should be carried out under real-life conditions such as the presence of water turbulence, suspended particles, wind and submerged objects with low reflectivity values. This will be necessary to assess the boundary conditions for which the method described in this paper can be applied.

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